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Your Golf Ball Isn't the Only Thing Going Into the Water: Examining Nutrient Enrichment in Aquatic Communities Downstream from Colorado Golf Courses

Michael Kenneth Jones
Michael.K.Jones@Colorado.EDU

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Examining Nutrient Enrichment in Aquatic Communities Downstream from Colorado Golf Courses

By
Michael Jones
University of Colorado at Boulder

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Thesis Advisors:

Dr. Carol Wessman, Ecology and Evolutionary Biology Department, Committee Chair
Dr. Pieter Johnson, Ecology and Evolutionary Biology Department
Dale Miller, Environmental Studies Program

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Abstract

This project examined whether or not runoff from golf courses in Colorado is contributing to nutrient enrichment and eutrophication in aquatic communities, similarly to agricultural runoff and sewage discharge. Existing political and scientific strategies were referenced in an effort and build a monitoring technique that has the potential for a solution that can bridge the gap between the golfing and ecological communities. Upstream and downstream water samples were collected from eight different golf courses in Colorado, and analyzed in the laboratory for concentrations of Total Nitrogen (TN), Total Phosphorus (TP), and turbidity. Downstream concentrations of TN and TP were significantly higher than upstream concentrations, while there was no difference in turbidity. Compared to the Environmental Protection Agency's "Ambient Water Quality Criteria Recommendations," only some golf courses were above the EPA's recommendations for TN and TP. Three different techniques were used to determine if each sampled course was an environmental concern, a potential environmental concern, or an unlikely environmental concern, with courses falling in each group. Golf courses could be an overlooked cause of eutrophication in aquatic communities, and further research is needed to conclude with greater statistical influence. This study encourages changes in golf course management on select courses and increased water sampling on all sampled courses, which will hopefully lead to a large increase in water quality around these courses. Golf courses present unique ecological opportunities and can act as areas of ecological refuge, if managed properly.

Preface

I'd like to begin by giving thanks to all of the wonderful people who made this possible. I think I'd like to give these thanks in the form of a cheers, or a toast to each person or group. Cheers, to the Undergraduate Research Opportunity Program, for providing financial flexibility for me, and allowing me to get all of my water samples analyzed professionally. Also, thank you UROP for having an early deadline, it was a nice kick in the rear to get started and get organized. Cheers, Dr. Carol Wessman, for the incredible mentorship you have offered throughout the process. You have been a calming voice when I have felt overwhelmed, a motivator when I was struggling, and most importantly, a person who has made me want to reach for bigger and better things, in science and in life. Cheers, Dale Miller, for persuading me to complete an Honors Thesis. You have been very influential in my personal growth, always acting as a facilitator that has provided me with opportunities to advance my schooling, and providing a foundation for me to be successful in life. Cheers, Dr. Piet Johnson, for inspiring me. You have been an unbelievable teacher and mentor, and I credit you with creating much of the scientific motivation that I have today. You have reminded me what is possible in this career, and have encouraged me to attain those heights. Cheers, Dr. Jason Neff, for mentioning golf course runoff as a source of eutrophication. Without you, I probably wouldn't have researched this topic or even known it existed. Cheers, Jim Self and the rest of the CSU Water Testing Lab, for completing my water testing analysis for me. Cheers, Scott Cline, for being an unbelievable golf coach, and friend, over the last few years. You have been a golf professional I can approach with any question, and talk about any topic with, even if it was negative, which is rare in that profession. Cheers, to the many golf professionals, superintendents, and executives, I was able to speak with over this process, including Ben Welsh, Neil Tretter, George Hart, Brent Barnum, Doug Cook, Derek

Rose, and to all the leaders of the courses I took samples from whom I did not get a chance to speak with. Golf is one of my many passions, and all of you allowed me to try and bridge the gap between environmental protection and golf course management. Cheers, Pemba Sherpa, for saying that Hole 11 smelled fishy, and for being an awesome person to be around. If you weren't so nice and outgoing, I might not have asked about your round, you might not have told me about the fish smell, and I wouldn't be writing this. Cheers, to my family who provides me with an incredible support system. All of you push me to aspire to new heights, and provide any assistance you have. Cheers, Dad, as you drove me all over the state collecting water samples, and reminding me, "I don't care if they don't want us to take samples, we're doing good science, and we're taking the samples we want." Cheers, Kristi Waring, for sacrificing a weekend to collect some water samples with me. You've been very supportive and understanding through the whole process, and I am incredibly grateful for that. And finally, cheers, to everyone else who may have impacted my progress during this time. If you are reading this and are unsure if you influenced my progress, the answer is yes; you did have a positive influence on me, no matter how small the action may have been.

I have always thought the best pieces of writing begin with a good story, so that is how I will start mine. Anyway, I can think of worse places to grow up than in Vail, Colorado. You'd be troubled to find an area that offers the amount of outdoor and recreational opportunities that Vail does. This area was the reason I fell in love with the outdoors, and the reason I have dedicated my education to learning how to protect, conserve, and manage our natural resources. While growing up there, one of the many activities I grew fond of was golf. Golf is not exclusive to Vail, as there are thousands of courses across the world, but the environmental awareness of golf courses that I now posses, was exclusively created by my upbringing in Vail. I spent my first 18

years living within 100 meters of an incredibly beautiful golf course, the EagleVail Golf Club. I have played over 500 rounds of golf on this one course, and probably know every intricacy of it better than the head greenskeeper. I not only know the golf course, but during the last three summers while I was working over 50 hours per week as an outside service member, I grew to know the hundreds of people who frequent this course. With my playing experience and working experience, I have arguably the most course knowledge and the most local tales as anyone who has ever stepped foot on the EagleVail Golf Club.

I began learning about environmental science in high school, and I always felt like the principles I was learning about were already ingrained in me. I was raised camping, fishing, hiking, golfing, and simply enjoying the natural environment. Environmental science became more interesting to me as I learned more, and soon I started wondering whether there were environmental costs or benefits associated with golf courses. I didn't really think much of this for the next several months until one lecture, in the spring of 2012, at the University of Colorado. I was taking an Introduction to Environmental Studies class, and the topic that day was eutrophication. I'll go into this more in the background section, but basically eutrophication is a process that causes algal blooms and possibly even "dead zones" in waterways associated with these algal blooms. These blooms can kill fish and other organisms that inhabit these waters, and are typically caused by anthropogenic (human) sources. My professor told us that sewage discharge, agricultural runoff, and even *golf course runoff* were common sources of eutrophication. I was intrigued by this statement, and wondered if EagleVail was experiencing or contributing to eutrophication. Again, I did not give this much thought until a summer afternoon in 2012.

On a beautiful July afternoon, one of our most likeable pass-holders at EagleVail had just finished his round and I quickly greeted him, which is the usual behavior for the outside service staff. I was asking about his round, and nothing was out of the ordinary, until he said, "Hole 11 fairway smelled really fishy today. I wonder what that is about." Hole 11 is a scenic hole at EagleVail, a Par 5 that has two large ponds down the right side of the fairway, and these drain into a creek that flows through the middle of the fairway, before going underneath Highway 6, and flowing into the Eagle River. Being the eager scientist and avid golfer I am, I played a round of golf the next morning in order to investigate the science of the golf swing and of eutrophication. Once I reached Hole 8, which is upstream on the same creek, from Hole 11, I started to notice a "fishy" smell. I walked down to the edge of the creek in front of the tee box, and noticed huge amounts of aquatic plants and algae were growing in the water, but I didn't see any dead fish. I wondered if I was seeing algal blooms associated with eutrophication. Then I reached Hole 11, and there I saw five belly-up fishes, accompanied by dense algal growth beneath the water surface. These fishes were floating in an eddy just before the stream exits the course, and I was lucky to see them at all.

Since then, my interest and knowledge of eutrophication from golf course runoff has grown. In addition to my academic responsibilities over the last four years, I also attempted to walk-on to the CU Men's Golf Team, and have played in over 20 competitive tournaments across the state. I love playing golf, and like most golfers I am addicted to the possibility of having your best round ever on any given day, which has led me to play countless rounds over the last 5-10 years; however, while most golfers are usually worried about their next shot, I have found that I am usually worried about the appearance of waterways and the threat of eutrophication around the course. After the day I saw dead fish in EagleVail, I have noticed dense algal growth in many waterways near various Colorado golf courses. These simple observations inspired me to complete my Senior Honors Thesis in Environmental Studies, researching this topic.

Introduction

The purpose of this project was to examine whether or not Colorado golf courses are contributing to eutrophication and affecting water quality in nearby aquatic communities. This project sought to determine if golf course runoff is another serious threat to eutrophication in aquatic communities, in addition to historical causes such as agricultural runoff and sewage discharge. I also hope this project will be used as the background for future implementations of better management practices (BMPs) for golf courses throughout the country and around the world. I investigated how nutrient enrichment differs between courses of different ecoregions and different course qualities (high or low), which allowed me to identify trends between the quality of a golf course, the ecoregion it is located in, and how each may relate to nutrient enrichment. The EPA defines ecoregions as "areas of general similarity in ecosystems and in the type, quality, and quantity of environmental resources," (EPA 2014a).

The question I researched was: Do aquatic communities downstream from Colorado golf courses exhibit concentrations of Total Nitrogen (TN) and Total Phosphorus (TP) that are significantly different than upstream concentrations, and are downstream concentrations above the EPA's recommended nutrient concentrations to limit eutrophication? I tested the hypothesis: Aquatic communities downstream from Colorado golf courses exhibit TN and TP concentrations that are significantly higher than upstream waters, and downstream concentrations of TP and TN are higher than EPA recommendations, while upstream concentrations are not.

In order to answer this question, I collected upstream and downstream water samples from eight golf courses in Colorado, tested each sample for TN and TP concentrations, and compared the upstream concentrations to the downstream, to determine if there were significant nutrient differences between upstream and downstream areas.

This Honors Thesis is written to fellow Environmental Studies students, miscellaneous science majors, other undergraduate students, or people with some previous knowledge of simple ecological, environmental, and biological principles; however, I have written my thesis in such a way that a person that has only graduated high school can grasp what I am studying and why it is important. Also, I hope that higher educated professionals, i.e. those with PhDs, will respect the depth I have displayed in my scientific endeavors. This paper is significantly detailed, yet I trust the points of this thesis can be summarized in an efficient manner, in order to reach a length that is publishable in scientific journals.

I expect golf professionals, golf course superintendents, and other business owners or managers to benefit from the underlying principles in this project. Golf courses are examples of places that may be causing nutrient enrichment in nearby aquatic ecosystems, but there are many more businesses that may be doing the same. These establishments may use the methods outlined in my project as the basis for collecting and testing water samples from nearby waters. Depending on results, these professionals may consult my paper in order to design and implement BMPs for their course or business. I intended for this project to help businesses and golf courses consider how they may be contributing to environmental degradation and lowering water quality, and how they can bridge the gap between successful business endeavors and environmental protection, ensuring both are accounted for.

This Honors Thesis presents the background and importance of this study, a review of past research, a description of my methods, a summary, analysis, and discussion of my data, and will include my conclusions and future recommendations for this field. I also included relevant figures and visuals to highlight my results. This project is the culmination of one academic year of research, under the supervision of my Honors committee.

Background

With an ever-increasing human population, and only a finite amount of accessible freshwater, managing and protecting freshwater resources is extremely important throughout the world. Together with concerns over declining fisheries, ocean acidification, global climate change, biodiversity losses, and others, minimizing or eliminating damage to aquatic ecosystems is critical to much of the human population. Worries over water quality have greatly increased over the last 60 or so years, and many professionals across the world have dedicated their careers to the goal of increasing water quality. This project is rooted in this larger goal of increasing water quality and decreasing environmental degradation. Eutrophication poses a threat to water quality and aquatic ecosystems, and is currently one of the most significant and observable forms of ecological change in the world (Ansari 2011; Johnson et al. 2007; Meleen 2003). In North America, 48 percent of all lakes are in the eutrophic state, and the United States alone spends $2.2 billion dollars per year combating the negative effects associated with eutrophic freshwaters (Ansari 2011). Many processes affect water quality, but my project studies the specific processes of eutrophication and nutrient enrichment, how these can affect water quality, and how golf courses may be contributing.

Every golfer steps onto a golf course and hopes for the following conditions: perfectly groomed and majestic grass from the tee to the green, with no weeds or imperfections in sight. Only the luckiest and wealthiest golfers in the world actually get to experience a course like that, but all golfers expect golf professionals and superintendents to try their very hardest to achieve those fantastical conditions for their course. Vast amounts of water, fertilizers, pesticides, and machinery are necessary to create a perfectly groomed course. Fertilizers are used to stimulate growth and success of the grasses, but when these chemicals enter nearby water systems, there can be harmful effects on aquatic ecosystems.

One of the major problems that occurs when fertilizers or excess nutrients enter aquatic ecosystems is a phenomenon known as eutrophication. The structure of many aquatic communities is determined by the amount of algae and other plants present, as these organisms are primary producers, which are at the bottom of the food web. The abundance and success of primary producers determines how much energy flows through an ecosystem. Because primary producers synthesize energy from the sun through photosynthesis, the growth of these organisms is significantly limited by essential nutrients, especially nitrogen and phosphorus, which is what most fertilizers are made of (Schindler 1974; Balogh and Walker 1992). Humans often add nutrients to freshwater communities through processes including runoff from farms or agricultural areas and discharging treated sewage into bodies of water (Meleen 2003). Nutrient enrichment greatly stimulates the growth of algae and other aquatic plants, which increases the primary productivity of the ecosystem. When primary producers rapidly multiply, many of these organisms also die, leading to a greater amount of food for aerobic decomposers, which allows aerobic decomposers to multiply. Aerobic decomposers consume dead organic matter, but also consume dissolved oxygen in the process (Meleen 2003). Therefore, with more aerobic decomposers present, the amount of dissolved oxygen decreases rapidly. Dissolved oxygen may get so low that almost no fish or other organisms can survive, which can create large dead zones (Meleen 2003). This cyclical process is known as eutrophication. On the other end of the spectrum, bodies of water that have low concentrations of nutrients and high water clarity are termed oligotrophic.

Eutrophication can be stimulated by runoff from golf courses. For example, the maintenance crew at a golf course may apply fertilizers to the course on any given day. Before the grass can take up all the nutrients, it begins to rain, or the sprinklers turn on, and some of the unused nutrients flow into nearby lakes and streams with the runoff. Now there is an unusually high amount of nutrients in the aquatic community, and the process of eutrophication begins.

Monitoring eutrophication in aquatic ecosystems is important for a variety of reasons. First, nutrient enrichment has been recently linked to increased disease transmission in a variety of wildlife species and in humans. Many scientists have found that the vector-borne human diseases malaria and West Nile virus, and others, may increase with nutrient enrichment (Johnson et al. 2010; Grieco et al. 2006; Grieco et al. 2007; Reiskind et al. 2004; Lawler et al. 2005; Miller et al. 2010). Increases in severity and transmission of coral reef diseases have been experimentally proven to increase with higher nutrient concentrations (Johnson et al. 2010; Bruno et al. 2003; Voss and Richardson 2006). Eutrophication has been proven to increase amphibian infection by the trematode parasite *Ribeiroia ondatrae,* which causes limb malformations and population declines in amphibians (Johnson et al. 2007). Second, large dead zones due to harmful algal blooms (HABs) may be caused by nutrient enrichment, and these can have detrimental economic and biological effects. Dead zones caused by hypoxia, or a lack of oxygen, have been noticed in over 400 systems worldwide, and now span an area of 245,000 km^2 (Diaz and Rosenberg 2008). These dead zones have caused large fish kills and have even led to the collapse of fisheries throughout the world (Diaz and Rosenberg 2008). Third, eutrophication has been linked with losses in biodiversity in aquatic ecosystems (Romanuk et al. 2006; Vitousek et al. 1997). One interesting study found that HABs led to the death of 21 Sea Otters in Monterey Bay, California (Miller et al. 2010). Sea Otters are a famous keystone species because they maintain the structure of kelp forest communities, and are responsible for maintaining the vast biodiversity in these communities. Fourth, eutrophication can lead to large economic losses throughout the world, including drinking water contamination and negative impacts to recreational industries such as swimming, boating, and fishing. These concerns, and many others, provide justification for why monitoring eutrophication and nutrient enrichment is important.

I designed this project to be the starting point for, hopefully, a blossoming relationship between the golfing and scientific communities. I attempted to bridge the gap between the two, and ensure each party's interests are accounted for. During my course selection phase, mentioned below, I spoke with many course professionals and superintendents. My research was received negatively overall, with most course leaders denying they were causing any water pollution, some questioning how algal growth is an indicator of nutrient enrichment, and some leaders simply refusing to let me take water samples. Also, I spoke to one superintendent who stated that he is part of a group of superintendents in the area, who have monitored nutrients in the past, and that his course, was "not causing any problems, and so we have since stopped testing the waters," (Tretter person. comm. 2014). I was discouraged from reaching out to other industry professionals, because of the responses I received from the ones I did speak with. With that in mind, I have left out the names of each course I sampled for privacy and confidentiality considerations. Courses will be labeled A-H, in order of collection (i.e. Course A was the first course I collected samples from, Course B was next, and so on, up through Course H).

Literature Review

I reviewed the current literature to increase my knowledge of nutrient runoff from golf courses and to become more comfortable with traditional methods in this field. This review is composed of a variety of scholarly sources, and will focus on limiting nutrients in freshwater ecosystems, how golf courses may increase the amount of nutrients in nearby water systems and evidence that it is occurring, whether or not water pollution from golf courses poses an environmental threat, differences in professional opinions, a review of similar studies unrelated to golf courses that will help contextualize my results, and a summary of past policy decisions regarding this topic.

Limiting Nutrients in Aquatic Ecosystems

Algae and other microorganisms are the drivers of eutrophication, and their growth is maintained by the amount of essential nutrients available. Like humans, microorganisms need adequate energy and resources to grow large and reproduce. Nitrogen and phosphorus are the most important nutrients in determining growth of primary producers. These organisms use nitrogen to build proteins and nucleic acids, and phosphorus is critical in energy reactions like photosynthesis and respiration (Balogh and Walker 1992). With higher nutrient concentrations, these organisms can grow larger and multiply, and cause eutrophication.

Phosphorus is largely viewed as the most important limiting nutrient in freshwaters (EPA 2000c). In one of the most famous eutrophication experiments ever conducted, a lake in Ontario, Canada, was split in half using a large vinyl and nylon divider. One half of the lake was fertilized with phosphorus, nitrogen, and carbon, and the other half was fertilized with just nitrogen and carbon. The half that was fertilized without phosphorus showed very similar abundances of microorganisms and plants before and after fertilization; however, the half that was fertilized with phosphorus showed much higher abundances of microorganisms and plants after fertilization. These results indicated that phosphorus was the primary cause of eutrophication (Schindler 1974). A review on eutrophication also stated that phosphorus was the most common cause of eutrophication in freshwater streams and lakes, whereas nitrogen was more effective at causing eutrophication in oceans (Correll 1998).

Nitrogen is also a significant limiting nutrient in freshwaters, however, especially in rivers and streams. In a nutrient enrichment experiment in a northern Ozark stream, scientists concluded that algal biomass was limited by nitrogen, not phosphorus (Lohman et al. 1991). Another study concluded that in Arizona, if algal production was determined by nutrient concentrations, nitrogen was often the most limiting nutrient (Grimm and Fisher 1986). Algal biomass in streams from sub-alpine, forested, agricultural, and urban areas in Australia, was limited primarily by nitrogen, and secondarily by phosphorus (Chessman et al. 1992). Researchers also concluded that algal growth in the Upper Spokane River was nitrogen limited (Welch et al. 1989). Runoff from golf courses may increase concentrations of both of these limiting nutrients. Most fertilizers are a combination of nitrogen, phosphorus, and potassium, which is why agricultural runoff has long been determined as a cause of eutrophication (Balogh and Walker 1992; Mueller and Helsel 1996).

One way to determine which nutrient is limiting is to calculate the mass ratio of Nitrogen to Phosphorus. By calculating mass ratios of N/P, you can determine the likelihood of cyanobacterial blooms (Ekholm 2008). Cyanobacteria are photosynthetic bacteria that are common in many aquatic ecosystems; however, cyanobacterial blooms can be very harmful to other organisms, as cyanobacteria can produce poisonous (Dodson 2005). N/P ratios above 17:1 indicate phosphorus is the limiting nutrient, N/P ratios between 10:1-17:1 indicate nitrogen and phosphorus are co-limiting, and N/P ratios below 10:1 indicate nitrogen is limiting. Cyanobacteria can fix (produce their own) nitrogen, and thrive in nitrogen-limited environments; therefore, it is important to monitor limiting nutrients in order to minimize cyanobacterial proliferation (Dodson 2005).

Evidence that Golf Courses Affect the Flow of Nutrients into Freshwaters

During my research, I was hoping to discover if golf courses have been noted to cause eutrophication like agricultural lands do. After reviewing the current literature, I believe there is reason to be concerned that golf courses also contribute to eutrophication in freshwater ecosystems. Many studies have been conducted to determine nutrient fluxes from golf courses into nearby waters. Scientists completed a study in Japan that measured the amount of nutrients entering a stream from an upper forested basin and a downstream golf course. The study stated that the nutrient loading rates (the amount of nutrients entering the stream) for nitrogen and phosphorus were 2.5 and 23 times higher, respectively, in the golf course versus the forested basin (Kunimatsu et al. 1999). Another similar study was conducted in Canada, where scientists compared annual exports of nutrients from golf courses and nearby forests. They found that golf courses were contributing twice as much nitrogen and phosphorus into nearby waters than the forests (Winter and Dillon 2006). In a study done in China, authors concluded that runoff from a nearby golf course was leading to concentrations of nitrogen and phosphorus in surrounding water systems that were well above contaminant limits (Wong et al. 1998). Over a five-year period in Texas, scientists observed whether runoff increased nutrient loading rates into surface waters near a golf course, and found phosphorus levels in the waters near the course were high enough to recommend large changes in management practices (King et al. 2007).

Other experts have created experiments to model how golf courses increase nutrient fluxes into water systems, instead of taking field measurements. For example, one scientist created experimental plots with almost identical conditions to that of a golf course, and tested how nutrients applied to the grass flowed into water systems through runoff. The scientist found that runoff led to concentrations of phosphorus that could easily lead to eutrophication (Shuman 2002). Another team of mathematicians created a model to quantify differences in nutrient concentrations in waters around golf courses, compared to if the course had not been built. They concluded that with environmentally conscious management practices, there would be a 148 percent increase in nitrogen concentrations, and a 24 percent increase in phosphorus concentrations, than if the land had remained untouched (Mankin 2000). After these findings, I began to wonder if these nutrient levels pose a serious threat to water systems.

Golf Course Runoff as an Environmental Concern

I reviewed multiple sources that stated golf course runoff could be leading to eutrophication. Looking again at the study from China, the scientists concluded that with current fertilizer application rates, the nutrient inputs from the golf course would undoubtedly cause adverse environmental impacts, including eutrophication as well as surface and ground water pollution (Wong et al. 1998). In Kansas, a study was done to test and establish BMPs on golf courses, in order to minimize nutrient runoff from golf courses into surrounding waters. Before the implementation of these BMPs, the scientists found nitrogen and phosphorus concentrations were high enough that eutrophic conditions could have existed, but the golf course was applying an algaecide (a chemical used to kill algae) to combat the problem (Davis and Lydy 2002). Another study examined different grass cultivation techniques, testing if these techniques could limit the amount of nutrients lost from fertilizers. Regardless of the cultivation technique used, the scientists found that the phosphorus levels in surrounding surface waters were still above EPA recommendations for nutrient levels (Rice and Horgan 2011).

It is evident that runoff from golf courses could be an environmental concern. The USGS (United States Geological Survey) stated that phosphorus levels are highest downstream of urban areas, and may lead to concerns regarding dissolved oxygen, eutrophication, and toxicity to fish (Mueller and Helsel 1996). As we have seen in these studies, golf courses also have very high concentrations of phosphorus in nearby waters, so we would expect that areas downstream from golf courses might experience concerns over dissolved oxygen, eutrophication, and toxicity to fish as well.

Differences in Professional Opinion

The sources I gathered during this review showed a general consensus and concern about nutrient runoff from golf courses; however, there were a few differences in opinion. Four sources concluded that golf courses did not pose significant threats to aquatic ecosystems. First, after reviewing studies done on 17 courses, three scientists concluded that widespread or repeated water quality harms were not occurring (Cohen et al. 1999). Second, a study of three courses in North Carolina led scientists to conclude the three golf courses were not affecting water quality, and found that nutrient levels were well below EPA recommendations (Ryals et al. 1998). These studies are contradictory to many of the other sources in this field, and these differences may be due to poor measurement techniques or other errors, but may also indicate differences in management practices, the amount of golf holes near water bodies, and other potentially different variables. Third, during a Congressional Hearing on the protection of wetlands, a golf course owner stated that golf courses protect the environment daily, and that the costs associated with implementing proper water management techniques were much higher than the potential damages wetlands may experience from golf course runoff (House of Representatives 1991). Fourth, another scientist concluded that water quality impacts from golf courses were generally positive, and that turfgrass systems should even be used as water treatment strategies (Watschke 1989). This leads me to believe these studies should be viewed as anomalies that are dissimilar of the field's total research, but may still be valid.

Based on the differences in professional findings, a useful approach to evaluating nutrient enrichment from golf courses is on a case-by-case basis, before any changes in management practices are introduced to specific courses. Many of the sources I reviewed looked at multiple courses at once rather than just one, which is why I am choosing to examine water samples from many different courses.

Relevant Studies to Help Contextualize Results

In order to put the results of my study in a greater context, I examined the results of a paper that observed ecological responses to nutrients in Colorado streams, and another study that developed limits for when TN and TP begin to influence algal biomass (Lewis and McCutchan 2010; Dodds et al. 2002). One pair of researchers sampled 74 streams throughout the mountains and foothills of Colorado, and tested each for TN, TP, and chlorophyll a, amongst other variables (Lewis and McCutchan 2010). They surveyed sites that did not have substantial nutrient pollution; in other words, they avoided agricultural lands, golf courses, urban areas, etc. Lewis and McCutchan (2010) determined that nutrient levels did not have a significant affect on algal biomass (measured by chlorophyll a), and that nutrient concentrations were secondary to other factors influencing algal growth, including elevation and time of year. The researchers observed nutrient concentrations that were below limits that would begin to influence algal growth (Lewis and McCutchan 2010). If concentrations are above these limits, nutrients are primary factors in controlling biomass, and if below, nutrients are secondary factors (Lewis and McCutchan 2010). Dodds et al. (2002) determined these aforementioned limits as greater than 40 μg/L for nitrogen, and greater than 30 μg/L for phosphorus (Lewis and McCutchan 2010; Dodds et al. 2002). The mean (average) TN concentration observed by Lewis and McCutchan (2010) was 0.376 mg/L. The mean TP concentration observed by Lewis and McCutchan (2010) was 26.5 μg/L. I used these findings to help determine the environmental concern for each single golf course I sampled, which I will discuss more in the methods section.

Past and Current Policies Regarding Water Pollution from Golf Courses

As of today, very few policies have been put into action to limit nutrient enrichment and eutrophication. The Clean Water Act has been very successful restoring and protecting many of our nations' water systems since it was created; however, the EPA has not established thorough nutrient requirements for aquatic communities. Originally, the EPA created the "Quality Criteria for Water," in 1986. These criteria were recommendations for the amount of nutrients that should be present per unit of water, yet the criteria had no regulatory impact and provided no incentive for land users to abide by them (EPA 1986). In 1990, Colorado Legislature passed the Agricultural and Groundwater Protection Act to encourage voluntary adoption of better management practices, including the proper use of fertilizers. This act did not have any regulatory power either, as it was encouraging voluntary changes, and was ineffective at greatly reducing pollution (Waskom 1994).

The EPA revisited this issue in 2000, and created "Ambient Water Quality Criteria Recommendations," for rivers and streams, lakes and reservoirs, and wetlands, across the United States (EPA 2000a; EPA 2000b). The purpose of these documents was to "provide technical guidance and recommendations to States, authorized Tribes, and other authorized jurisdictions to develop water quality criteria and water quality standards under the Clean Water Act (CWA) to protect against the adverse effects of nutrient overenrichment," (EPA 2000a; EPA 2000b). The documents also stated, "Even though [these documents contain] EPA's scientific recommendations regarding ambient concentrations of nutrients that will protect aquatic resource quality, it does not substitute for the CWA or EPA regulations, nor is it a regulation itself. Thus it cannot impose legally binding requirements on EPA, States, authorized Tribes, or the regulated community, and it might not apply to a particular situation or circumstance," (EPA 2000a; EPA 2000b). This basically says, the EPA has developed nutrient recommendations for different areas across the country, but allows the State or Tribe to develop and enforce their own water quality standards.

These documents were created in December of 2000, and in fourteen years, States across the U.S. have done very little to implement nutrient criteria. As of 2014, the State of Colorado has established phosphorus and chlorophyll-a (a measure of algae) criteria for two lakes and three reservoirs, but has not established nitrogen criteria for any lakes or reservoirs, or nitrogen, phosphorus, or chlorophyll-a criteria for any rivers or streams (EPA 2014b). The EPA projects Colorado will still have the same minimal nutrient criteria until at least 2016; however, the State of Colorado has compiled potential nutrient criteria for all lakes, reservoirs, rivers, and streams, but the EPA is still reviewing the criteria (EPA 2014b). It is worth noting that other States have established nutrient criteria within one year after submitting potential nutrient criteria to the EPA, so it is possible that Colorado will establish nutrient criteria before 2016, but I was not able to locate any evidence to support this (EPA 2014b). Without policy changes, it is likely that water bodies throughout the U.S. will still experience the negative effects of eutrophication.

Methods

While conducting my background research, I was able to review a variety of sources, and design my project based on traditional techniques. Based on my research on policies, I decided I would use the EPA's "Ambient Water Quality Criteria Recommendations," and all corresponding documents as the technical basis of my methods, especially the EPA's "Nutrient Criteria Technical Guidance Manual: Rivers and Streams." I have described the methods I used during this project, and will support them with research on each technique.

The methods I used as the basis of my research allowed for two different outcomes to occur. First, I could analyze whether golf courses, as a whole, were contributing to downstream nutrient enrichment, which is what I am trying to determine in this study. But secondly, it allowed me to analyze which specific courses were the most environmentally concerning, and to then make recommendations for each individual course. It is worth noting this unique and innovative aspect of my study, as both large-scale and small-scale problems can be addressed.

Phase 1: Variable Determination

The EPA recommends testing water samples for causal and response variables. Causal variables are defined as TN and TP, and response variables are chlorophyll-a and turbidity (EPA 2000c). Turbidity is a measure of water clarity, and chlorophyll-a is a measure of algal biomass (EPA 2000c). TN and TP are causal variables because they *cause* algal biomass to increase, while turbidity and chlorophyll-a are response variables because they *respond* to the causal variables, and increase or decrease accordingly.

Nitrogen and phosphorus are the main nutrients that lead to changes in primary productivity in aquatic ecosystems. Due to differences in professional opinion on the most important limiting nutrient, as mentioned in the literature review section, I chose to monitor both concentrations of TP and TN, as the causal variables (EPA 2000c).

The EPA's "Ambient Water Quality Criteria Recommendations" suggest different nutrient criteria for different Ecoregions and Subecoregions (also known as Level III Ecoregions) across the United States. I collected water samples from two Ecoregions in Colorado, with four golf courses in each Ecoregion. The nutrient criteria offered for Subecoregion 21, a more specific area of Ecoregion II, where four of the courses were located, included recommendations for turbidity, but did not include recommendations for chlorophyll-a; therefore, I chose to measure turbidity as the response variable in all of my water samples (EPA 2000a). The specifics of how the EPA established specific nutrient concentrations are explained in greater depth, in the discussion section.

I decided to monitor TP and TN as my causal variables instead of nutrient loading rates, nitrate, ammonium, and soluble phosphorus levels, or other variables. Although these variables have been emphasized in past studies, I chose to build my project around existing political framework (Kunimatsu et al. 1999; Winter and Dillon 2006; Wong et al. 1998; Rice and Horgan 2011). By designing my project in this way, I was able to monitor variables that were recommended by the EPA and the State of Colorado. This allows for the opportunity of future political regulation of the variables I monitored, which in turn allows for potential increases in monitoring, and hopefully necessary changes in management practices in the future, as we attempt to minimize this issue.

Phase 2: Course Selection

I chose eight different golf courses in Colorado from which to collect water samples from. I selected each course by a haphazard (not quite random) search on Google Earth, where I scanned nearby areas for golf courses that had the criteria described below. Four courses were located in Ecoregion II, Subecoregion 21, near Vail, Colorado (EPA 2000c). The other four courses were located in Ecoregion V, Subecoregion 25, in the Denver-Boulder area of Colorado (Figure 1) (EPA 2000b). I chose to take water samples from courses near Vail, because that is where this whole idea stemmed from and I had some familiarity with each course. The courses I sampled in Denver and Boulder were selected because I live in Boulder, and it was easier to take samples from courses near me.

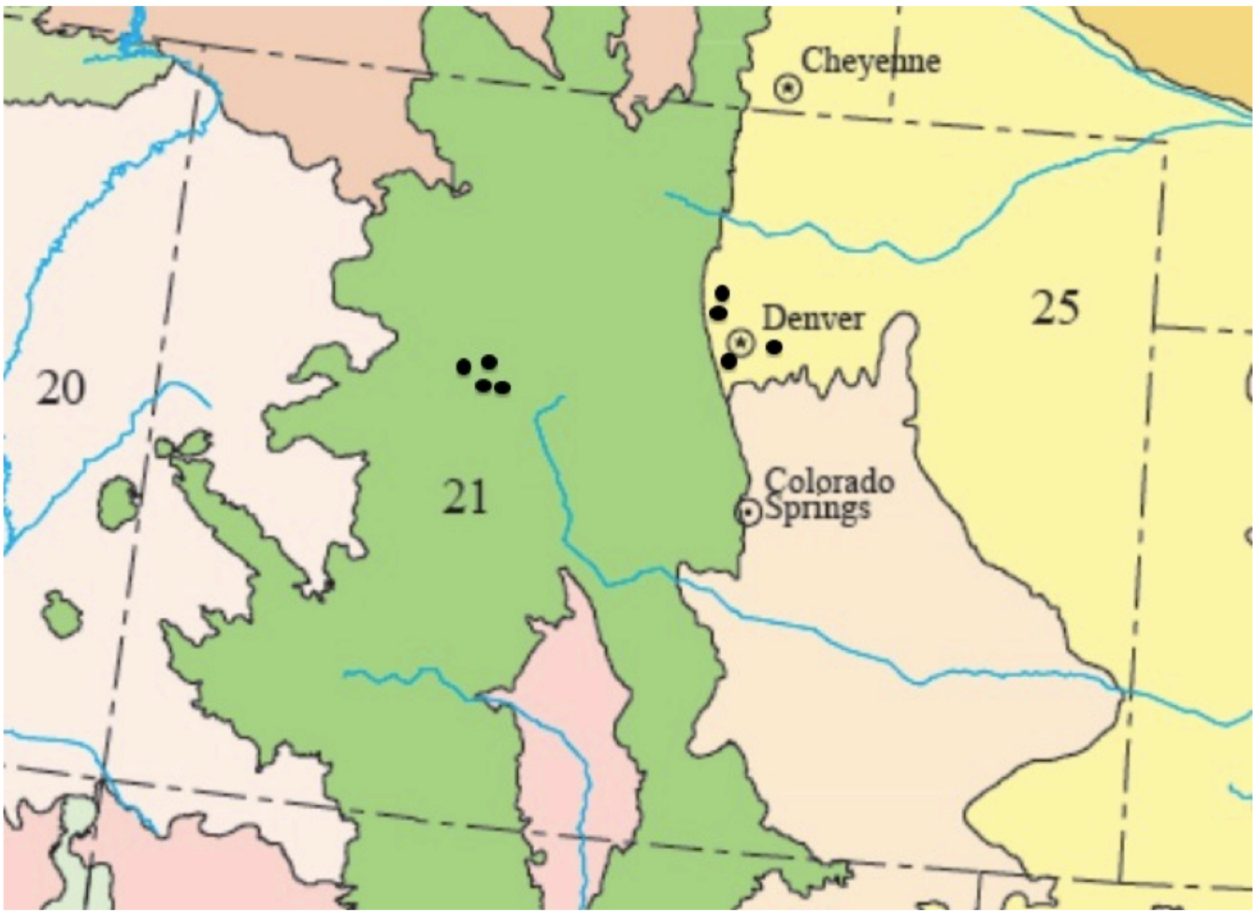

Figure 1: Ecoregional map of Colorado, with eight sample golf courses. The black dots represent the approximate locations of the golf courses I sampled. Ecoregion II contains Subecoregion 21, and Ecoregion V contains Subecoregion 25, as shown.

I selected each course based on a two characteristics. First, of the four courses in each Ecoregion, two were of "high" quality and two were of "low" quality. Second, each course had a definable stream running through long stretches of the course. Golf courses are very large areas of land, and each one is unique in many ways. Because of that, controlling variables is very difficult; however, I used those characteristics to both control variables, and to possibly identify trends between Ecoregion, course quality, and how each might affect nutrient enrichment.

I defined high and low quality based on public accessibility, cost of play and personal observations. If the course was a private country club, or a semi-private club, it was deemed to be high quality, whereas if it was a public golf course, it was deemed to be low quality. Golf courses that are private or semi-private clubs tend to spend much more time, money, and resources, grooming the turf to look perfect. By trying to increase the quality of the turf, these courses tend to use more fertilizers. Second, I determined courses were of low quality if the maximum cost to play one round, was under $100. All four low quality courses fall into that category, and price to play one round at the semi-private courses is much more expensive. Third, I have played each course in Ecoregion II, and the two public courses in Ecoregion V, and have talked to many people about each course. It is commonly agreed that the two semi-private clubs in Ecoregion II are of much higher quality than the two public courses. Of the courses in Ecoregion V, I believe the two courses I have played are not high quality, and other playing partners I have had, have voiced similar opinions. The two high quality courses in Ecoregion V were determined to be high quality by one course's PGA Tour event history and overall reputation, and the other by personal communication from a golf professional in the area (Cline person. comm. 2014).

Courses within the same Ecoregion were grouped together, with two high and two low quality courses in each Ecoregion. I chose to do this to try and isolate the variable of course quality. This way, I could compare the high quality courses to low quality courses, and determine whether course quality created a large difference in nutrient enrichment or not. I tried my best to use courses that were geographically near one another, with each course less than thirty miles from all other Ecoregional courses.

Each course had a very obvious stream running through or along large stretches of the course, which I determined initially through aerial observations using Google Earth and confirmed with field observations during my sample collections (Figure 2). Based on my sampling techniques, which I will discuss below, I needed golf courses that had continuous running water above the course, throughout the course, and below the course. These streams traveled from areas where I expected low nutrient runoff, the upstream areas, to areas where I expected high nutrient runoff, the downstream areas, which is consistent with EPA recommendations on how to monitor nutrient enrichment (EPA 2000c).

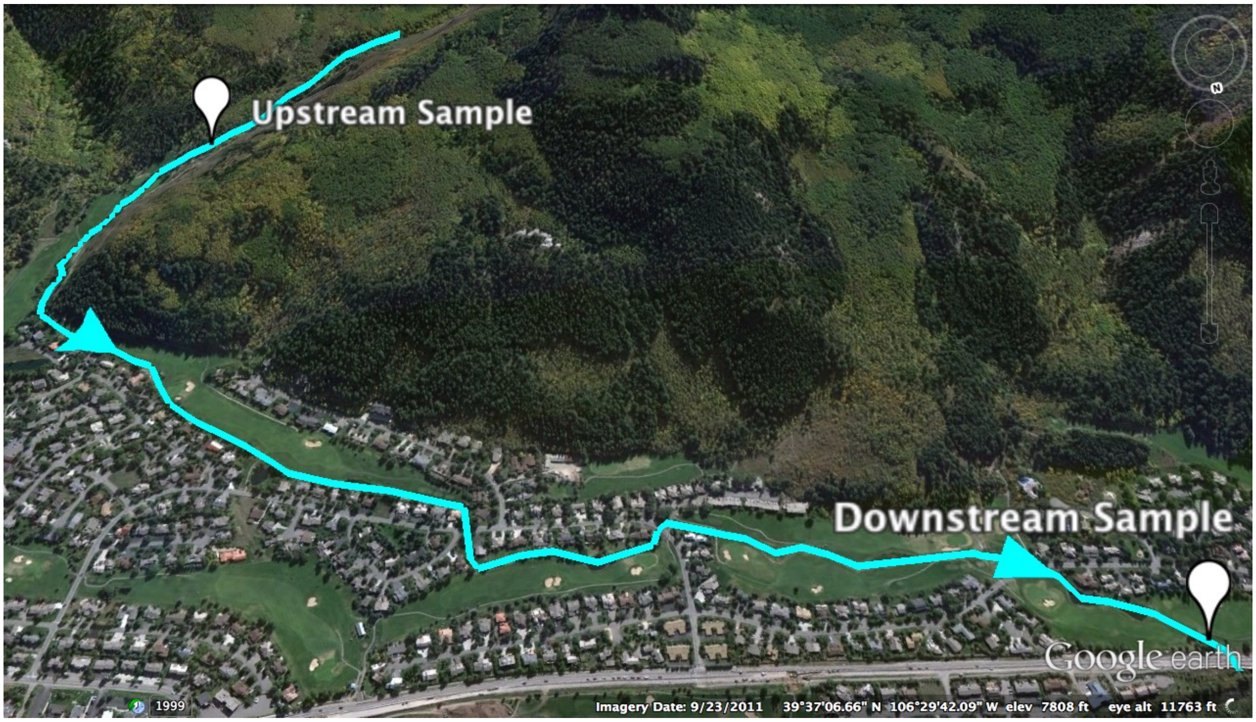

Figure 2: An aerial photograph, courtesy of Google Earth, of Golf Course D. The upstream and downstream sample sites are noted, as well as the stream direction with arrows. The rest of the aerial photographs have been attached in the appendices.

Phase 3: Sample Collection

I collected water samples from eight different golf courses in Colorado. I believe golf courses may be major sources of nutrients in streams, and therefore I took samples from upstream and downstream from each course. This technique was based on the EPA's technical recommendations and historically relevant studies in this field (EPA 2000c; Kunimatsu et al. 1999). One water sample was collected upstream from each course and one was collected downstream from each course. Additional samples were not collected due to high costs associated with water testing.

Water samples were collected during low-flow conditions in the fall of 2014. I selected this time of year because of sampling ease, but also because I expected this time of year to have the greatest amount of nutrient enrichment, as the courses had been open for months and fertilization was frequent throughout the season (EPA 2000c). Additionally, low-flow conditions allowed for minimal dilution, which would likely produce higher concentrations of nutrients than during high-flow events.

All water samples were grab samples, collected from the middle of the stream, at mid-depth (APHA et al. 2012). My sampling protocol was the same for every site. Upon my arrival to the golf course, I surveyed both of the sites I wanted to collect samples from, made sure there was enough water to collect a sample, and observed the conditions of both waterways. I took each downstream water sample first, so I did not create any disturbances that may have flowed downstream to my other sample. Before sampling, I took notes on the clarity, depth, width, flow, and presence of wildlife in each body of water. I also observed the condition of each golf course, including overall conditions of the waterways, buffer regions, and topography. I collected these notes in my field notebook, and later created a data table with all field notes (Table 1). When sampling, I rinsed the 1-liter sampling bottle and cap with the water downstream from my site (APHA et al. 2012). To sample, I submerged the 1L bottle facing the current, unscrewed the cap, filled it, and fastened the cap before reemerging (APHA et al. 2012). I made sure to steer clear of excess turbulence in the water, in order to avoid misleading results (APHA et al. 2012). I labeled each sample and put it on ice, upon returning to the car (APHA et al. 2012). All samples were kept on ice until I transported them to the Colorado State University Soil, Water, and Plant Testing Laboratory, within 48 hours of collection. The first eight water samples were collected on October 18th and October 19th, and transported to the CSU Lab on October 20th. The following eight water samples were collected on October 26th, and transported to the CSU Lab on October 27th.

Phase 4: Laboratory Analysis

The Colorado State University Soil, Water, and Plant Testing Laboratory performed all laboratory analysis of my water samples. All of my samples were tested initially for turbidity, TN, and TP, between October 27th, 2014, and December 5th, 2014. They were then retested for TN and TP, between December 5th, 2014, and February 13th, 2015. The CSU Laboratory completed analyses according to EPA Standard Methods. After the implementation of the Clean Water Act, the EPA published these standard methods, instructing how to measure chemicals and biological pollutants in various water sources, including surface water.

The concentrations of Total Nitrogen were calculated using EPA Standard Method 351.1. A colorimeter is a machine that determines which specific wavelengths of light are being absorbed by a specific substance. This procedure began by calibrating the colorimeter with standard solutions, to create a standard curve (EPA 1978). This means that a variety of solutions of known nitrogen content, were analyzed using the colorimeter, and the individual measurements were plotted onto a graph. A line of best fit was produced from the individual points, making a standard curve and a corresponding equation. Following the calibration, a sulfuric acid solution, containing potassium sulfate and mercuric sulfate, in order to convert all organic nitrogen to ammonium sulfate, was added to the water sample (EPA 1978). Next, a sodium hydroxide solution was added, followed by an alkaline phenol regent, which forms a blue color, noted as indophenol (EPA 1978). The blue color of indophenol is what allows the colorimeter to determine concentrations of TN, as the color is different depending on the concentration of TN. This new solution was then analyzed using the colorimeter, and the colorimeter value was recorded (EPA 1978). Next, the colorimeter value from the sample was plugged into the standard curve equation, and the amount of TN in the water sample was calculated from the curve (EPA 1978). The procedure was repeated twice for each sample, and then retested twice more, during the second round of testing.

Total Phosphorus concentrations were calculated using EPA Standard Method 365.4. Like the calculation of TN, this procedure used a standard curve created after measuring standard colorimetric solutions. A solution containing sulfuric acid, potassium sulfate, and mercuric sulfate was added to the water sample, and then the new solution was heated for 2.5 hours (EPA 1974). Next, the solution was cooled, and diluted using distilled water (EPA 1974). Then, the solution was analyzed by the colorimeter, and the unknown value was calculated using the standard curve equation (EPA 1974). The procedure was repeated twice for each sample, and then retested twice more, during the second round of testing.

Each water sample was tested for turbidity, according to EPA Standard Method 180.1. A machine called a nephelometer, which measures the intensity of light that is scattered by a given solution, calculates turbidity (EPA 1993). With higher intensity of scattered light, the solution is more turbid, and vice versa (EPA 1993). The procedure began by allowing each sample to reach room temperature, and then the sample was thoroughly mixed to disperse the solids (EPA 1993). Second, the water sample was poured into a tube, then placed into the nephelometer, which displayed the turbidity value of the sample (EPA 1993). This was repeated twice for each water sample, within 48 hours of sample collection. Turbidity was only measured during the first testing cycle, and was not retested along with TN and TP.

Phase 5: Statistical Analysis

In order to determine if nutrient concentrations downstream from golf courses were different than upstream concentrations, I performed a series of statistical tests. First, I examined the distribution of my data graphically, and determined that I would perform a Base-Ten

Logarithm Transformation of my data to help meet standard assumptions of normality necessary for many parametric statistical tests (Lütkepohl and Xu 2012). All of the Base-Ten Logarithm Transformations were calculated using Microsoft Excel. For this transformation, I took the Base-Ten Logarithm of each value and added one, because many of my values were below one, and a Base-Ten Logarithm Transformation of a number less than one, would lead to an error in Excel. For example, for the first upstream value of TN on Course A, the transformed value would be:

$$\text{Log10}(0.12+1) = 0.0492$$

After transforming all of my data values, I ran two-tailed, paired t-tests on the upstream and downstream values of TN, TP, and turbidity, using the statistical software JMP. A two-tailed, paired t-test determines whether or not the researcher should reject their null hypothesis, which states that there is no difference between two groups in the same population (Bonamente 2013). A two-tailed, independent t-test examines if there is a difference between groups of different populations. Because all of my samples were taken from the population: all golf courses that fit my course selection criteria, and I was analyzing different groups within that population (i.e. upstream and downstream), I chose to use a two-tailed, paired t-test. The null hypotheses in my study state that there are not significant differences between the upstream and downstream values for TN, TP, and turbidity, given a confidence interval of 95 percent. My alternative hypotheses are that the downstream values are significantly different than the upstream values of TN, TP and turbidity, given a confidence interval of 95 percent. The two-tailed, paired t-test tells us whether it is 95 percent probable that of the given population: all golf courses in the world that fit my course selection criteria, the difference between mean downstream and upstream concentrations would be zero, if a given sample size was collected, given the null hypothesis is true (Bonamente 2013). This is signified by a value known as the P-value, which falls between zero and one. If the P-value is less than 0.05, the data are *statistically significant* and the null hypothesis should be rejected, in favor of the alternative hypothesis (Bonamente 2013). If it were higher than 0.05, then the null hypothesis would not be rejected, and the alternative hypothesis would be rejected.

Analysis of Variance (ANOVA) tests are used to evaluate how X affected Y. I performed ANOVA tests to assess whether course quality, Ecoregion, and the interaction between the two, had a significant affect on nutrient concentrations downstream from the eight golf courses. The results of these tests are also indicated by a P-value, and determine statistical significance in the same manner as the paired t-tests.

Phase 6: Determination of Environmental Concern for Each Sample Course

By designing my project the way I did, it also allowed me to make conclusions about the individual courses I sampled. I used three different techniques to determine my level of environmental concern for each individual course. First, I examined whether or not the downstream concentrations of TN and TP of each course were above the EPA's recommendations, for each round of laboratory testing (Table 6). I looked at courses based on, 1) if the downstream concentrations of TN and TP were above EPA recommendations for both rounds of testing, 2) if the downstream concentrations of TN and/or TP were above EPA recommendations for one or both rounds of lab testing, but not both TN and TP for both rounds of testing, 3) if the downstream concentrations of TN and TP were below EPA recommendations for both rounds of testing. This procedure allowed me to compensate for the discrepancies between the data sets, which I will address in the discussion section.

The second technique I used to determine the environmental concern of each sample course was a comparison against the recommendations of the Dodds et al. (2002) study, and the findings in the Lewis and McCutchan (2010) study, both mentioned in the literature review. Recall that the Dodds et al. (2002), established concentration limits that indicate when nutrients begin to influence algal growth, switching from secondary to primary factors controlling biomass (Dodds et al. 2002; Lewis and McCutchan 2010). I also compared my nutrient concentrations to the mean values observed by Lewis and McCutchan (2010) to situate each value amongst a much greater sample size. Values that were above both Dodds et al. (2002) limits and Lewis and McCutchan (2010) mean values, were the most concerning to me, and was the second technique I used to determine the environmental concern of each course.

Lastly, I calculated the mass ratios of nitrogen to phosphorus, as this can be an indicator of potential cyanobacterial growth, which can be very environmentally damaging, as I mentioned in the literature review (Ekholm 2008).

From these three techniques I grouped the courses together into three different categories. I determined the nutrient concentrations from both rounds of laboratory testing to be most important, and then considered comparisons to the Dodds et al. (2002) limits and Lewis and McCutchan (2010) mean values, and mass ratios of N/P, as less important than nutrient concentrations, but equally important to one another.

Results

The following section is the compilation of the field observations from my two sampling trips, the field data results I received from the CSU Soil, Plant, and Water Testing Laboratory, as well as the results of my statistical analysis, and the determination of environmental concern of each course. I included the data sets from both rounds of laboratory tests. I only performed statistical analysis on the data from the first laboratory tests, which is displayed in the following pages.

Field Observations

While collecting water samples, I took detailed observations of each golf course. I noted aspects including water clarity of the upstream and downstream sample sites, presence of wildlife, depth, width, flow, conditions of other water bodies, buffer regions, topography, and others. I also added observations based on my previous experiences playing four of the eight courses. Just to clarify, I am not a plant biologist or experienced in phycology (the study of algae), so many observations state simply that there were "aquatic plants or algae present in the water," which was the level to which I was comfortable describing the underwater plant growth. I have provided a table that summarizes the basic observations I made during my sample trips (Table 1). Below, I will discuss the most pertinent observations I took; the complete field observations are found in Appendix I.

The sample collection process yielded some interesting and puzzling observations. First, while collecting samples at Course B, I observed three large (50-200 m^2) lakes on three consecutive holes, and noted the condition of each. These lakes possessed algal growth on the surface, abundant plant growth near the shoreline, and appeared eutrophic overall, especially when compared to a nearby lake (Figure 8). Before taking samples there, I spoke with the superintendent of Course B, and ended up using his recommendations for the locations of the upstream and downstream sample sites. The upstream sample site was an irrigation ditch, which is diverted off of a nearby creek that provides water for the neighborhood around Course B. The downstream site was a discharge from a drainage pipe, which ran underneath a road and emptied into a ravine, from a pond on the first golf hole.

The downstream sample site at Course C contained an extremely large amount of algae and other aquatic plants, and was almost covering the entire creek bottom. I was actually surprised by how much was growing in the creek. To investigate further, I walked to where this creek entered into a larger creek below the end of the golf course. The larger creek was really clear, with hardly anything growing in it, and yet, just fifty yards upstream, the smaller creek possessed abundant aquatic plants.

At Course D, I had the most interesting of all of my observations. In the downstream sample area, there looked like there used to be dense algae or aquatic plants, but it appeared that it all had died off, and became brown or lifeless (eutrophication perhaps?). After seeing this, I walked 50 meters upstream from the downstream sample site, and there were massive amounts of aquatic plant growth throughout the creek, the largest underwater growth I observed. I saw this only fifty meters upstream from the downstream sample site, which made me wonder if I was witnessing a dead zone. I did not see anything living in the creek at the downstream site, as the whole thing was extremely clear, but it seemed like nothing was moving or alive (Figure 3). In my years of playing Course D, I have observed many trout in this area of the creek and a variety of macroinvertebrates. The downstream sample site was where I originally saw the five dead fish, and I was struck by the lack of life in that area, thinking back to the day with the fish.

Course E is a course I am very familiar with, and I have seen unique organisms while playing golf and collecting the water samples. There is an extensive lake/stream system that flows through many of the last nine holes, where I have noticed both frogs and turtles within the lakes. I also observed tadpoles in a nearby drainage ditch near my upstream sample site.

The upstream sample area at Course F appeared to be more of a canal and less of a natural occurring stream, and I wondered what effect this might have on my results. This water was extremely murky, only about 15 cm deep, and I could not see the bottom. There were many leaves in the water, and the water was pretty unattractive overall; the secretary at the CSU lab even picked up the sample and said, "ew, this one is yucky." I did notice water striders on the surface, but the clarity and overall condition of the water made me doubt that many native large organisms were living in this.

The last two samples were collected from arguably the best course in Colorado, in most golfers' eyes. Downstream, I did notice some algae on some rocks, but not as much as I expected. The course has very fast greens (short grass), with no buffers on any of the waterways. There were some very severe slopes that went directly into the sample creek, and these had very tightly mown turf all the way to the shoreline, which would likely lead to more nutrient runoff. The course is unbelievably beautiful and well maintained. It hosted a PGA Tour event this year, the US Amateur Championship in 2013, and US Open Championships in the past (all very popular and important golf tournaments). I attended the PGA event this year, and observed many of the water bodies while I was there. The course is famous for a lake on holes 17 and 18, and I did not observe any algal growth in the water, which was unexpected.

Table 1: Table of Field Observations. This summarizes the basic observations I took during my sampling trips. The Golf Course column indicates the course and the sample location (i.e. "A – Up" signifies Course A, upstream sample site). The asterisks state that those were previous observations, and that I did not see those organisms during my sampling trips.

Golf Course	Water Clarity	Aquatic Plant/Algal Growth	Flow	Wildlife	Depth/Width
A – Up	Low clarity	None seen	Fast	Did not see wildlife	40cm / 2 m
A - Down	Too shallow to tell	Abundant, covering all rocks in water	Fast	Did not see wildlife	30 cm / 4 m
B - Up	Clear but shallow	Debris from nearby trees, no growth in water	Relatively Fast	Water strider	15 cm / 1.5 m
B - Down	High clarity	Did not see any, fallen leaves on surface	Fast	Did not see wildlife	150 cm / 5 m
C - Up	High clarity	Algae/aquatic plants present, not abundant	Very Fast	Did not see wildlife	60 cm / 7 m
C - Down	Too shallow to tell	Algae/aquatic plants very abundant	Relatively Fast	Did not see wildlife	30 cm / 2 m
D - Up	High clarity	None, mosses on rocks above surface	Very Fast	Many macroinvertebrates	40 cm / 3.5 m
D - Down	High clarity	None seen at sample area	Slow	Trout*, macroinvertebrates	30 cm / 3 m
E - Up	High clarity	Fallen grasses from shore, none in water	Relatively Fast	Dragonfly, tadpole*, turtle*	30 cm / 1 m
E - Down	Low clarity	A few aquatic plants, not abundant	Slow	Did not see wildlife	15 cm / 4 m
F - Up	Low clarity	Fallen grasses from shore, none in water	Fast	Did not see wildlife	100 cm / 5 m
F - Down	Very low clarity	Did not see any, water too murky	Very slow	Water strider	15 cm / 3 m
G - Up	Low clarity	Algae abundant on submerged rocks	Very slow	Many macroinvertebrates	3 m / 20 m
G - Down	High clarity	Algae/aquatic plants present, not abundant	Very Fast	Many macroinvertebrates	60 cm / 7 m
H - Up	Low clarity	Algae present in faster water	Slow	Macroinvertebrates present	60 cm / 8 m
H - Down	Clear but shallow	Some algal growth, not abundant	Slow	Did not see wildlife	30 cm / 4 m

Figure 3: Graphic from the downstream sample site at Course D, and 50 meters upstream. The bottom photo was where my sample was actually collected, and the top is from 50 meters upstream of the sample site. Notice the large changes in algal biomass and water clarity, even though the sites were close by, and the depths were the same. Could the bottom picture be a dead zone?

Laboratory Test Results

Water quality analyses are summarized in Table 2 (first round) and Table 5 (second round). The units used for each measurement are, milligrams per liter for Total Nitrogen (mg/L), micrograms per liter for Total Phosphorus (μg/L), and nephelometric turbidity units for turbidity (NTUs). When I completed the statistical analysis of the data set below, I switched the values of <0.01 to 0.01 (Table 2). This allowed me to complete the statistical analysis, since JMP needs exact numbers to perform analysis.

Table 2: Laboratory test results from the first round of laboratory testing. "Up S" and "Down S" signify upstream and downstream, respectively. TN is Total Nitrogen and TP is Total Phosphorus.

Golf Course	Quality	Ecoregion	TN - Up S (mg/L)	TN - Down S (mg/L)	TP – Up S (μg/L)	TP – Down S (μg/L)	Turbidity - Up S (NTU)	Turbidity - Down S (NTU)
A	Low	II	0.12	0.15	18.3	116	7.2	2.5
D	Low	II	<0.01	<0.01	26.9	26.1	0.5	1.0
B	High	II	<0.01	0.28	8.0	23.9	0.6	0.6
C	High	II	<0.01	0.39	<0.01	8.0	0.7	0.9
E	Low	V	<0.01	0.04	20.1	44.1	1.5	2.1
G	Low	V	<0.01	<0.01	<0.1	21.9	2.2	2.0
F	High	V	<0.01	<0.01	24.9	531	4.1	40.1
H	High	V	0.14	0.82	46.1	8.0	1.2	1.2

Tables 3 and 4 show the EPA's recommended values for the two Subecoregions that the golf courses I sampled were located in. Notice there are substantial differences in recommended values between the two Ecoregions.

Table 3: EPA Recommendations for Ecoregion II (EPA 2000a).

EPA Recommendations: Ecoregion II, Subecoregion 21	
Total Nitrogen	0.09 mg/L
Total Phosphorus	6.34 μg/L
Turbidity	1.65 NTU

Table 4: EPA Recommendations for Ecoregion V (EPA 2000b).

EPA Recommendations: Ecoregion V, Subecoregion 25	
Total Nitrogen	1.07 mg/L
Total Phosphorus	60 μg/L
Turbidity	12.60 NTU

Table 5: Laboratory test results of the second round of laboratory testing. Turbidity values are still the same as the first round, since they were not retested. "Up S" and "Down S," signify upstream and downstream, respectively. These results also show data to three decimal places, for TN, and one decimal place for TP, which differs from the first round of testing.

Golf Course	Quality	Ecoregion	TN – Up S (mg/L)	TN - Down S (mg/L)	TP – Up S (μg/L)	TP – Down S (μg/L)	Turbidity – Up S (NTU)	Turbidity – Down S (NTU)
A	Low	II	0.941	1.088	72.4	60.8	7.2	2.5
D	Low	II	0.099	0.085	6.2	7.1	0.5	1
B	High	II	0.439	0.609	28.4	41.7	0.6	0.6
C	High	II	0.270	0.122	9.3	17.4	0.7	0.9
E	Low	V	0.001	0.124	10.1	0.1	1.5	2.1
G	Low	V	1.738	0.227	15.1	122.3	2.2	2
F	High	V	0.527	0.631	38.4	41.7	4.1	40.1
H	High	V	0.091	1.737	118	6.5	1.2	1.2

Results of Statistical Analysis

I performed two tailed, paired t-tests on the upstream vs. downstream Base-Ten Logarithm Transformed values of TN, TP, and turbidity. The first two-tailed, paired t-test indicated the downstream values of TN were significantly higher than upstream values, as shown by a P-value of 0.0373, and a t-statistic of 2.0934, from a sample size of 16 (Figure 4). The second two-tailed, paired t-test also indicated the downstream values of TP were significantly higher than upstream values, as shown by a P-value of 0.0299, and a t-statistic of 2.2431, from a sample size of 16 (Figure 5). The third two-tailed, paired t-test indicated there was not a significant difference between the upstream and downstream values for turbidity, as shown by a P-value of 0.2360, a t-statistic of 0.7599, from a sample size of 16 (Figure 6).

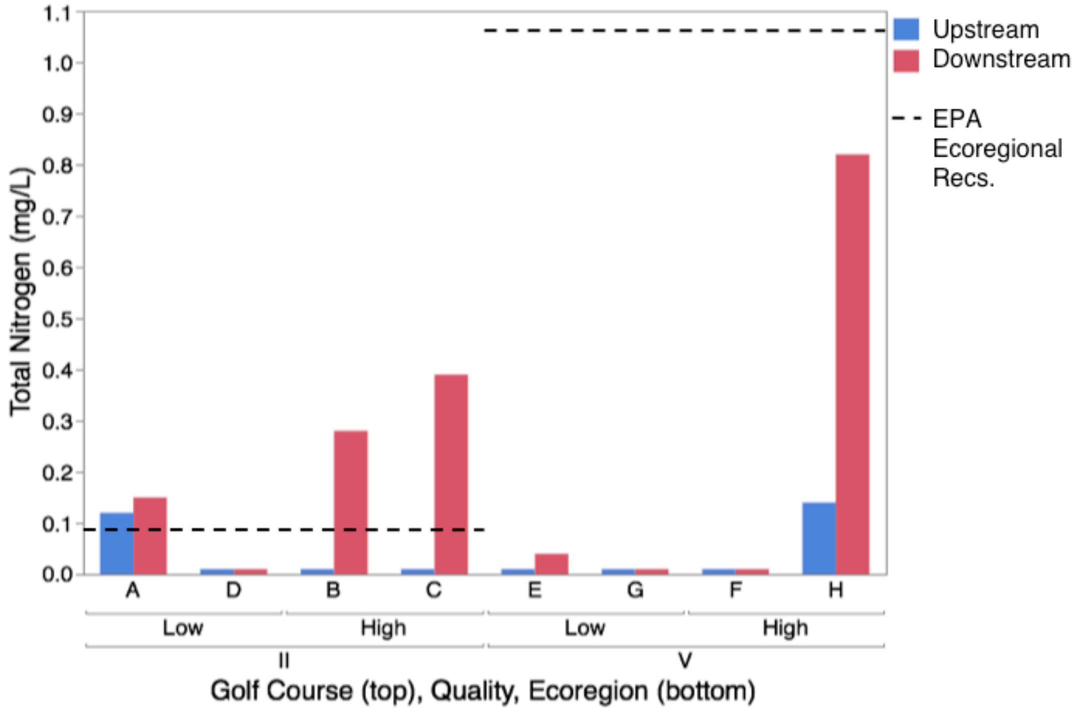

Figure 4: Upstream and downstream concentrations of Total Nitrogen. The dotted lines indicate the EPA's Ecoregional recommendations for TN. The x-axis shows golf course (A-H), quality (low/high), and Ecoregion (II and V). After a Log10 Transformation of the data values, a two-tailed paired t-test was performed to test whether downstream values were significantly different than upstream values. The downstream concentrations of TN were significantly higher than upstream concentrations, shown by a P-value of 0.0373, from a sample size of 16, and a t-statistic of 2.0934.

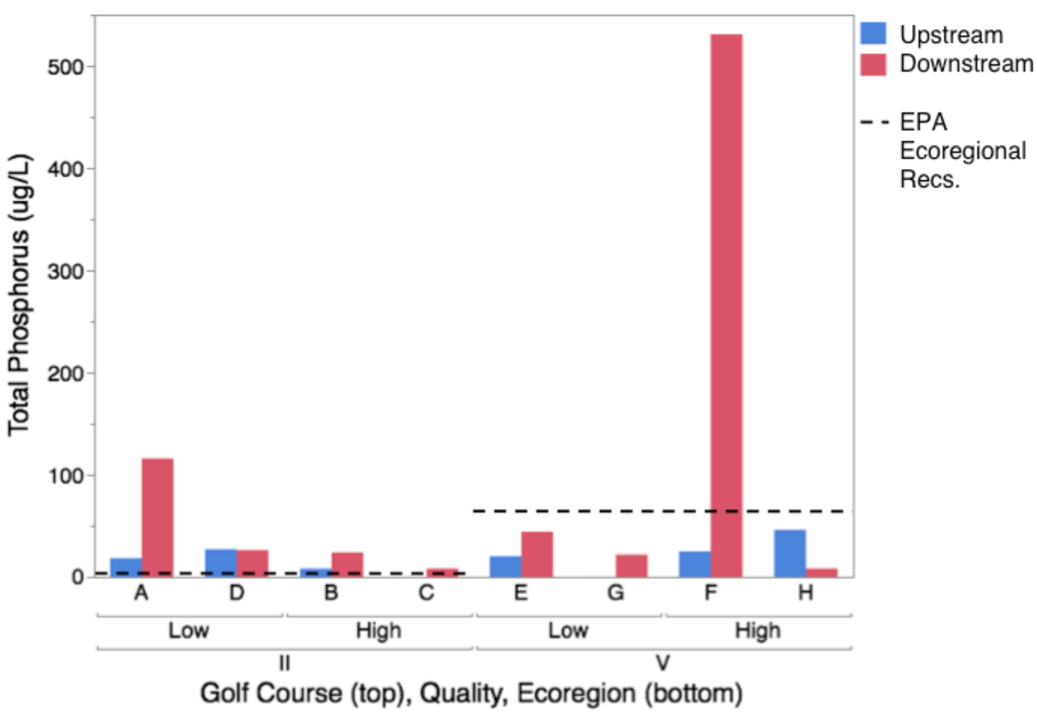

Figure 5: Upstream and downstream concentrations of Total Phosphorus. The dotted lines indicate the EPA's Ecoregional recommendations for TP. The x-axis shows golf course (A-H), quality (low/high), and Ecoregion (II and V). After a Log10 Transformation of the data values, a two-tailed paired t-test was performed to test whether downstream values were significantly different than upstream values. The downstream concentrations of TP were significantly higher than upstream concentrations, shown by a P-value of 0.0299, from a sample size of 16, and a t-statistic of 2.2431.

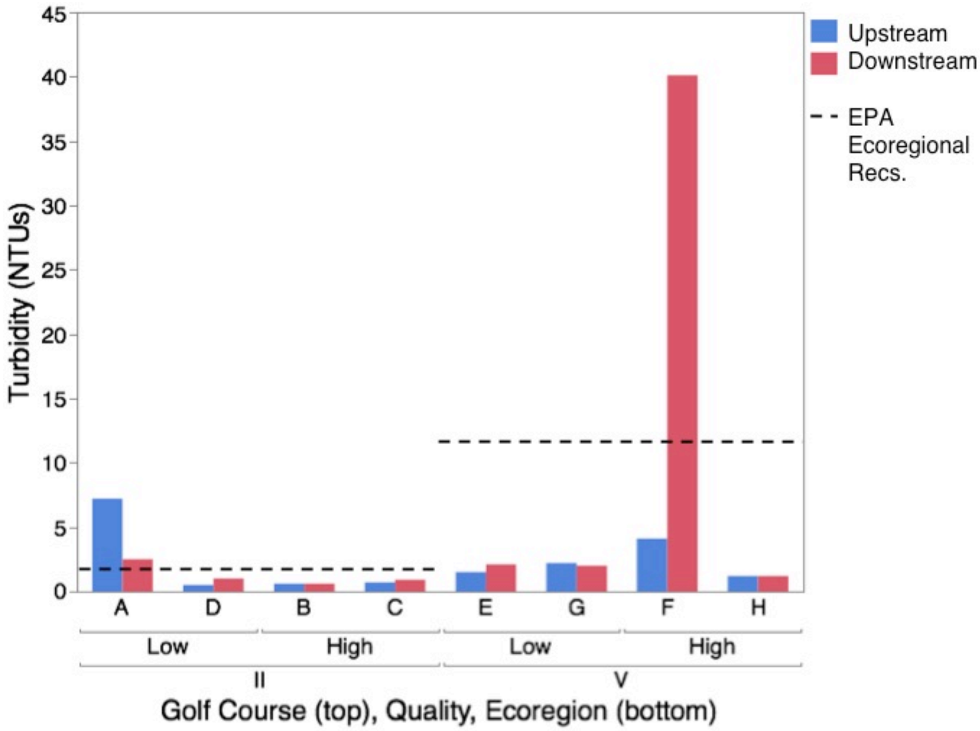

Figure 6: Upstream and downstream turbidity levels. The dotted lines indicate the EPA's Ecoregional recommendations for turbidity. The x-axis shows golf course (A-H), quality (low/high), and Ecoregion (II and V). After a Log10 Transformation of the data values, a paired t-test was performed to test whether downstream values were significantly higher than upstream values. The turbidities of downstream waters were not significantly different than upstream waters, shown by a P-value of 0.2360, from a sample size of 16, and a t-statistic of 0.7599.

Once I completed each paired t-test, I determined which samples were above the EPA's Ecoregional recommendations. In the first round of laboratory analyses, the upstream and downstream samples of Course A, and the downstream samples of Courses B and C were all above the EPA's Ecoregional recommendations for TN (Figure 4). The upstream and downstream samples of Courses A, B, and D, and the downstream samples of Courses C and F were all above the EPA's Ecoregional recommendations for TP (Figure 5). The upstream and downstream samples of Course A, and the downstream sample of Course F were all above the EPA's Ecoregional recommendations for turbidity (Figure 6).

ANOVA tests were completed to determine if Ecoregion, course quality, or the interaction between them, affected downstream nutrient concentrations, and turbidity. Course quality, Ecoregion, and their interaction, did not have significant affects on downstream concentrations of TN, TP, or turbidity, as the P-values of each test were well above the 0.05 threshold; however, there were positive trends between course quality and TN, and course quality and TP, with the high quality courses having greater downstream concentrations of TN and TP, compared to the low quality courses. These trends were not significant, but were worth noting.

Determination of Environmental Concern Results

Below are the results of my determination of environmental concern system, described in the methods section. First, I determined whether the downstream values of TN and TP for each course were above or below EPA recommendations, for each round of laboratory testing (Table 6).

Table 6: TN and TP compared to EPA recommendations from both rounds of laboratory tests. This table indicates whether the downstream value of each course was above or below EPA recommendations, after the first and second lab testing rounds, completed by the CSU Soil, Plant, and Water Testing Laboratory. This table displays the first technique I used to determine the environmental concern I have for each course I sampled.

Golf Course	TN vs. EPA - 1st Round	TN vs. EPA - 2nd Round	TP vs. EPA - 1st Round	TP vs. EPA - 2nd Round
A	Above	Above	Above	Above
D	Below	Below	Above	Below
B	Above	Above	Above	Above
C	Above	Above	Above	Above
E	Below	Below	Below	Below
G	Below	Below	Below	Above
F	Below	Below	Above	Below
H	Below	Below	Below	Below

Next, I compared my results to the limits established by Dodds et al. (2002) and the mean and maximum concentrations of TN and TP observed by Lewis and McCutchan (2010) (Table 7). All of the sample courses showed downstream TN values above Dodds et al. (2002) limits, and TN downstream of Courses C and H, and TP downstream of Courses A, E, and F, were above the mean concentrations observed by Lewis and McCutchan (2010). Also, TP downstream from Course F exceeded the maximum value observed by Lewis and McCutchan (2010) in their 74 samples. These results indicate that TN concentrations downstream of every course, and TP concentrations downstream of Courses A, E, and F, were great enough to be the primary factor influencing algal biomass. Additionally, five of my sixteen downstream concentrations were greater than the mean concentrations of the Lewis and McCutchan (2010) results, which was a much larger sample size.

Table 7: Comparison table of results to results of previous relevant studies. The downstream values of TN and TP are displayed for each golf course. The values that are underlined are above Dodds et al. (2002) limits that state nutrients will not be a primary influence of algal growth, indicating those values will influence algal growth. The values that are bolded are above the mean values observed in the Lewis and McCutchan (2010) study. The values that are italicized (only Course E, TP) are above the maximum values observed by Lewis and McCutchan (2010).

Golf Course	TN - Downstream (mg/L)	TP – Downstream (μg/L)
A	0.15	**116**
D	0.01	26.1
B	0.28	23.9
C	**0.39**	8
E	0.04	**44.1**
G	0.01	21.9
F	0.01	***531***
H	**0.82**	8

I then calculated the mass ratios of N/P to determine the limiting nutrient in each water sampled, which allowed me to infer whether or not cyanobacterial blooms, which are harmful, would likely be present (Table 8).

Table 8: Mass ratios of N/P for all downstream samples. N/P ratios help determine the limiting nutrient in aquatic communities. The bolded values state that nitrogen is limiting, indicating that cyanobacteria would likely proliferate in those communities.

Golf Course	N/P Downstream
A	**1.29**
D	11.72
B	**0.38**
C	**1.25**
E	**0.91**
G	**0.46**
F	**0.02**
H	102.50

Finally, I grouped courses together based on the environmental concern I have for each, based on the three aforementioned techniques (Table 9).

Table 9: The levels of environmental concern for each sampled golf course. Downstream concentrations of TN and TP, comparisons to findings in Dodds et al. (2002) and Lewis and McCutchan (2010), and mass ratios of N/P were considered in order to determine the level of concern.

Environmental Concern	Potential Environmental Concern	Unlikely Environmental Concern
Course A	Course E	Course D
Course B	Course F	Course H
Course C	Course G	

Course A was distinguished as an environmental concern, as 1) TN and TP were above EPA recommendations, for both rounds of laboratory testing, 2) downstream TP was above the mean TP value observed by Lewis and McCutchan (2010), and downstream TN and TP were above the Dodds et al. (2002) limits for nutrients as a cause of algal biomass increases, and 3) the mass N/P ratio was lower than 10, indicating nitrogen is limiting, and cyanobacteria may be present (Table 6; Table 7; Table 8; Table 9). This course is of the highest environmental concern, according to my analysis, of all my sample courses.

Course B was distinguished as an environmental concern, as 1) TN and TP were above EPA recommendations, for both rounds of laboratory testing, 2) downstream TN was above the Dodds et al. (2002) limit for nutrients as a cause of algal biomass increases, and 3) the mass N/P ratio was lower than 10, indicating nitrogen is limiting, and cyanobacteria may be present (Table 6; Table 7; Table 8; Table 9). Downstream TP was not above the Dodds et al. (2002) limit, and downstream TN and TP were not above the mean values observed by Lewis and McCutchan (2010).

Course C was distinguished as an environmental concern, as 1) TN and TP were above EPA recommendations, for both rounds of laboratory testing, 2) downstream TN was above the mean TN value observed by Lewis and McCutchan (2010), and downstream TN was above the Dodds et al. (2002) limit for nutrients as a cause of algal biomass increases, and 3) the mass N/P ratio was lower than 10, indicating nitrogen is limiting, and cyanobacteria may be present (Table 6; Table 7; Table 8; Table 9). Downstream TP was not above the Dodds et al. (2002) limit, and downstream TP was not above the mean values observed by Lewis and McCutchan (2010).

Course E was distinguished as a potential environmental concern, as 1) downstream TP was above the mean TP value observed by Lewis and McCutchan (2010), and downstream TN was above the Dodds et al. (2002) limit for nutrients as a cause of algal biomass increases, and 2) the mass N/P ratio was lower than 10, indicating nitrogen is limiting, and cyanobacteria may be present (Table 6; Table 7; Table 8; Table 9). Downstream TP and TN were not above EPA recommendations, for either round of laboratory testing, and downstream TN was not above the mean values observed by Lewis and McCutchan (2010); however, with the aforementioned results, Course E could potentially be an environmental concern.

Course F was distinguished as a potential environmental concern, as 1) downstream TP was above EPA recommendations, for the first round of laboratory testing, 2) downstream TP was above the mean and maximum TP value observed by Lewis and McCutchan (2010), and downstream TN and TP were above the Dodds et al. (2002) limit for nutrients as a cause of algal biomass increases, and 3) the mass N/P ratio was lower than 10, indicating nitrogen is limiting, and cyanobacteria may be present (Table 6; Table 7; Table 8; Table 9). Downstream TP was not above EPA recommendations, for the second round of testing, and downstream TN was below EPA recommendations for both rounds of laboratory testing. Also, downstream TN was not above the mean values observed by Lewis and McCutchan (2010); however, with the aforementioned results, Course F is a potential environmental concern.

Course G was distinguished as a potential environmental concern, as 1) downstream TP was above EPA recommendations, for the second round of laboratory testing, 2) downstream TN was above the Dodds et al. (2002) limit for nutrients as a cause of algal biomass increases, and 3) the mass N/P ratio was lower than 10, indicating nitrogen is limiting, and cyanobacteria may be present (Table 6; Table 7; Table 8; Table 9). Downstream TP was not above EPA recommendations, for the first round of testing, and downstream TN was below EPA recommendations for both rounds of laboratory testing. Additionally, downstream TN and TP were not above the mean values observed by Lewis and McCutchan (2010); however, with the aforementioned results, Course G is another potential environmental concern.

Course D was distinguished as an unlikely environmental concern, as 1) downstream TN was below EPA recommendations, for both of laboratory testing, and downstream TP was below EPA recommendations for the second round of testing, 2) downstream TN and TP were below the mean values observed by Lewis and McCutchan (2010), and downstream TP was below Dodds et al. (2002) limit for nutrients as a cause of algal biomass increases, and 3) the mass N/P ratio was higher than 10, indicating nitrogen and phosphorus are co-limiting, and cyanobacteria may be present, but not likely abundant (Table 6; Table 7; Table 8; Table 9). Downstream TP was above EPA recommendations, for the first round of testing, and downstream TN was above Dodds et al. (2002) limit for nutrients as a cause of algal biomass increases; however, with the aforementioned results, Course D is unlikely to be an environmental concern.

Course H was distinguished as an unlikely environmental concern, as 1) downstream TN and TP were below EPA recommendations, for both rounds of laboratory testing, 2) downstream TP was below the mean values observed by Lewis and McCutchan (2010), and below Dodds et al. (2002) limit for nutrients as a cause of algal biomass increases, and 3) the mass N/P ratio was higher than 17, indicating nitrogen is limiting, and cyanobacteria are may be absent (Table 6; Table 7; Table 8; Table 9). Downstream TN was above Dodds et al. (2002) limit for nutrients as a cause of algal biomass increases, and mean TN values observed by Lewis and McCutchan (2010); however, with the aforementioned results, Course H is unlikely to be an environmental concern.

I will give my personal recommendations for each course in recommendations section, which will help course managers, of these courses and others, determine areas they can focus on and management strategies they can change or implement.

Discussion

My discussion section will consist of an analysis of my results compared to previous studies. I will mention studies based on golf courses and greater limnological (study of inland waters) concepts, and how they are reflected in my results. Results that surprised me, a reflection on EPA recommendations, and possible limitations to this project will also be included, and I will recommend future research for this field as a whole.

Results Compared to Previous Studies

The results of my study are consistent with previous studies focused around golf courses. First, the significantly higher downstream concentrations of TN than upstream concentrations are constant with the conclusions made by Kunimatsu et al. (1999), Wong et al. (1998), and Winter and Dillon (2006), as each of those studies observed increases in nitrogen near golf courses, compared to nearby areas. Second, the significantly higher downstream concentrations of TP than upstream concentrations agree favorably with the results from Kunimatsu et al. (1999), Wong et al. (1998), Winter and Dillon (2006), and King et al. (2007). These studies found increased concentrations of phosphorus near golf courses compared to neighboring areas. The lack of significant differences between upstream and downstream concentrations of turbidity is also consistent with EPA observations (2000c), as many different factors contribute to turbidity, other than nutrient concentrations and algal biomass.

After analyzing my results I also wanted to ensure I was not overlooking any major limnological concepts that might explain my results, other than nutrient enrichment from each golf course. One concept that I was particularly interested in is called the River Continuum Concept. This revolves around the idea of stream order, which classifies streams by their relative position in the watershed (Dodson 2005). For example, streams closer to the headwaters (beginning of the river) are given lower orders (i.e. 1-3), while streams furthest from the headwaters are given higher orders (i.e. >3) (Dodson 2005). Streams of higher order are typically wider, more turbid, and have higher nutrient concentrations, while lower order streams are less wide, less turbid, and have lower nutrient concentrations (Dodson 2005). Higher order streams also have a greater amount of autochthonous material (organic material originating from inside the stream, like algae), while lower order streams have less autochthonous material and more allochthonous material (organic material originating from outside the stream, like fallen leaves from terrestrial trees) (Dodson 2005). The idea is that lower order streams are light limited, because there are more terrestrial plants and trees shading the water, which limits photosynthesis in the water column, which in turn, lowers the amounts of autochthonous material in the water (Dodson 2005). Higher order streams overcome this issue with increased width, allowing for light to reach the water column, and stimulate growth of autochthonous material (Dodson 2005). This could explain the increased algal and plant biomass I observed in many of the downstream sites, as the downstream sites were not light limited because they were at the bottom of an area that was running through the golf course, where trees were not abundant (Table 1; Figure 2; Appendix II). Many of the upstream sample sites were in areas where trees were abundant, and could explain the lack of algal biomass I observed (Table 1; Figure 2; Appendix II). As for explaining the nutrient differences between the upstream and downstream sample sites, I believe the River Continuum Concept does not likely apply. First, the concept discusses nutrient increases in terms of increases in stream order, and none of the streams I sampled increase in order between my upstream and downstream samples sites, because I was taking samples from the same streams for the upstream and downstream samples (Figure 2; Appendix II). Second, the distance between my upstream and downstream samples sites were small, compared to the distances at which stream order differences will show effects described by the River Continuum Concept (Dodson 2005). For example, in the watershed map below, stream order changes take place on the 7-15 km scale, and the largest distance between my upstream and downstream sample sites was 2.56 km, at Course C (Figure 7).

Unexpected Results

After determining the environmental concern of each course, I was surprised by a few results. First, I was baffled that Course D was one of the lowest environmental concerns, according to my method of determination. This is the EagleVail Golf Club, where I've seen dead fish (see preface), where I've seen possible dead zones (Figure 3), and where I believed I would see the largest impact from nutrient enrichment. Other factors besides nutrients could have caused these events, as noted by other professionals, but I am cautious to fervently place Course D into the "Unlikely Environmental Concern" group (Lewis and McCutchan 2010; Detmer person. comm. 2015). As I will mention in the recommendations section, further research should be completed on all the courses I sampled, including Course D.

Second, I was surprised that Course H was also distinguished as an "Unlikely Environmental Concern." This course hosted a PGA Tour event this year, and it is likely that the course was being fertilized even more than during a normal year. One interesting point to mention, is this course had significantly reduced phosphorus levels downstream, compared to upstream. I observed many of the waterways, and there were no buffers whatsoever between the short, groomed, turfgrass, and the water surface. In terms of management practices, the lack of buffers should have led to increases in nutrients, especially on a course of that quality. I again will discuss this in the recommendations section, but this lack of nutrient enrichment could be attributed to other management practices, unrelated to buffers.

EPA Recommendations as a Source of Hope, Not Despair

Upon completing the analysis of my results, I began to feel optimistic about the potential mitigation of this problem on a countrywide scale. First, to give the political side some background, I will explain what the EPA's nutrient recommendations, which I've been referencing through the whole paper, actually mean. The EPA has been taking stream samples in all Ecoregions throughout the country over the last several years, at least since 1990 (EPA 2000a; EPA 2000b; EPA 2000c). They have analyzed samples for TN and TP, and either turbidity or chlorophyll a, or both, and compiled them into large datasets for each Ecoregion (EPA 2000a; EPA 2000b; EPA 2000c). From these datasets, they determined the lower 25th percentiles (meaning one quarter of the Ecoregional samples they analyzed fall below this value), as the nutrient recommendations to limit eutrophication (EPA 2000a; EPA 2000b; EPA 2000c). So those 25th percentiles are what I have been referring to as EPA recommendations, during this whole study.

These EPA recommendations, when compared to my results and the Lewis and McCutchan (2010) results, make me believe that the EPA is on the way to making large-scale improvements. First, only three out of eight, and five out of eight, of my downstream samples for nitrogen and phosphorus, respectively, tested above EPA recommendations. Considering golf courses have been attributed to increasing nutrient concentrations in local streams in Texas, Japan, Canada, and China, it is striking that only a handful of the downstream concentrations are above recommendations (King et al. 2007; Kunimatsu et al. 1999; Winter and Dillon 2006; Wong et al. 1998). Second, when compared with mean values observed by Lewis and McCutchan (2010), Ecoregional II EPA recommendations, where most Lewis and McCutchan (2010) sites were, the recommendations are well below their mean values. Also, when compared to Ecoregion V EPA recommendations, where a few Lewis and McCutchan (2010) sites were, mean values observed by Lewis and McCutchan (2010) are only higher in TN. This leads me to believe that if the EPA, or individual state legislators, enforced these recommendations across the country, we would likely see large reductions in eutrophic water bodies. The EPA has the opportunity, and the framework in place, to make vast improvements in this field, and now just needs to act.

Possible Limitations of This Study

Other factors, aside from nutrient runoff from each golf course, could explain my results. First, when completing studies such as this one, researchers typically try to control as many variables as possible, so they can determine whether or not what they were looking at was actually being explained by what they were testing. In my case, I wanted to determine if golf course runoff was increasing the amount of nutrients in the water downstream; however, it was extremely difficult to control all variables. While I tried to control for geographic locations, definable streams, time of year, and sampling techniques, several factors were not controlled. These included the distances between upstream and downstream samples sites, elevation changes between upstream and downstream sample sites, flow rate and volume differences between all samples sites, presence of ponds between sample sites, nearby neighborhoods that could affect nutrient levels, climate, management techniques on each golf course, and others. Those issues are common when thinking about a study of this scale. The land use around each course will be different, and no golf course in the world is like another, so trying to minimize the variables I mentioned above is nearly impossible; however, I do believe the system I used to determine each course allowed for as minimal variance.

Another potential limitation was my sample size, as it was very small, statistically speaking. In statistics, with a greater amount of samples collected by the researcher, the data will be more indicative of actual conditions. For example, I only sampled eight different golf courses, so it is difficult for me to make a statement about golf courses in general. What if these courses are anomalies, and other courses have lower or higher nutrient concentrations? With a greater sample size, questions like that become easier to answer, and the results of the study are more indicative of the entire issue, not just a subset of the issue.

The downstream concentration of TP from Course F was extremely high, compared to the rest of the data (Figure 5). This could have led to a statistical bias, as this value may have swayed the data to become more significant, because TP for that particular sample was so large. To compensate for this problem, I ran an additional paired t-test for TP, but omitted Course F entirely from the analysis. When I did this, the P-value I obtained was slightly above significant, at 0.0694. Because this value is still very close to 0.05, it is plausible that this value does not detract from the dataset, and its statistical significance, as a whole.

As noted in the methods section, samples were collected during low flow conditions in October of 2014, which may have led to higher nutrient concentrations than during other times of the year. In the fall, there is minimal dilution in the waterways I collected samples from. Spring runoff from snowmelt would likely lead to lower concentrations of nutrients, had I collected samples earlier in the growing season. All of the courses I sampled had been open for at least five months prior to my sample collection, and nutrient concentrations in my samples may have been higher than what are typically normal concentrations in those waterways; however, further research is necessary to examine this claim.

The CSU Soil, Plant, and Water Testing Laboratory could have been another possible limitation of this study. If I were to describe my confidence in the abilities of the CSU laboratory in one word, I would choose "uncomfortable." I delivered my first 8 water samples to the lab on October 20th, 2014, and the second 8 water samples to the lab on October 27th, 2014. In order to be viewed as accurate by the EPA, the samples have to be analyzed for TN and TP with 28 days of sample collection (EPA 2000c). I obtained the results from the first round of testing on December 5th, 2014, or 46 and 39 days after I delivered each sample set. This was particularly upsetting, because I believe the strength of my study comes from the interaction and consideration of both political and scientific methodology, and this led to my data falling outside the EPA's timeframe. This was the main reason why I chose to statistically analyze the first round of laboratory testing data. The data were sent with incorrect units and I received one dataset that was not mine, when they sent the first round of data. After I notified them of the issues, they sent me another revised dataset, which had a large value for TP for one of the upstream samples (450 μg/L). I notified them of that, they retested it, and found the TP concentration was actually less than 0.01 μg/L (very different). After discussing these issues with my committee chair, Dr. Carol Wessman, I asked the CSU lab to rerun every sample. They completed this and sent me the results on February 13th, 2015. This dataset, which was from the exact same samples, was completely different than the first one (Table 2; Table 5). I believe this lab could have been a source of error in my study; however, they are professionals in this field, and I would like to believe that the results I was given were indeed accurate. I also altered my results section to reflect these discrepancies, which I already mentioned.

Future Research for this Field

I recommend the future of this field should pursue research that will help clarify the ecological and aesthetic importance of golf course runoff. During my research, I found myself asking two questions throughout the process. First, I wondered whether or not nutrient enrichment from golf courses has watershed, or even larger scale, effects that I did not monitor. Second, do most people, or any people, look at golf course streams and ponds the same way as I do, and are they impacted by murky, eutrophic water? I believe before golf courses change management practices, research should be focused toward answering those questions.

Whether or not golf courses are influencing nutrient concentrations in aquatic ecosystems may depend on many different factors, as I have noted above. The ecological impacts on a much larger scale, say that of a watershed, may depend on many factors also. Each individual golf course presents a new challenge on how to properly manage water features and limit nutrient enrichment; however, I believe the real ecological challenge is how to monitor these effects on a large scale. For example, on one golf course, there may be a small stream and a series of small ponds. Each of these water features could be experiencing nutrient enrichment, and each drain into a larger stream or body of water, and those bodies of water drain into even larger ones. Most streams and ponds on courses are not used for fishing, swimming, drinking, etc, but if these waterways lead to damaging effects to aquatic ecosystems that are used for these activities, there would be a much larger demand to change management practices.

Therefore, I believe in addition to monitoring nutrient enrichment on individual courses, research efforts should focus on monitoring how golf courses could lead to larger scale issues. I believe this may be more important, because although each golf course possesses a series of aquatic communities, the problems associated with many courses with nutrient enriched communities could lead to effects that are greater than isolated algal blooms and fish kills. Runoff from many courses in one watershed, could lead to expansive fish kills, drinking water contamination, losses in recreation, and other harmful costs to local citizens. For example, in the Eagle River watershed, which is in Ecoregion II, there are 16 golf courses within the watershed, including four of my sample sites (Figure 7). The effects caused by one golf course may not be noticed on a watershed scale. But if all 16 courses are comparable to the course examined by the Kunimatsu et al. (1999) study, and are all discharging water that is 2.5 and 23 times higher in nitrogen and phosphorus, respectively, than if the courses were not there, there could be detrimental effects on watershed scale. As far as I know, this type of watershed-scale analysis of golf course runoff has not been conducted, and I believe future research should emphasize examining effects on this scale.

Another topic I believe should be researched in the future is the determination of the aesthetic importance of oligotrophic versus eutrophic golf course streams and ponds. I look at golf courses, and the waterways that occupy them, in a unique way. While growing up, I became accustomed to seeing lakes and rivers that were several meters deep, deep blue in color, and had very high water clarity. To me, golf course waterways should be clear, not murky. Whether other people feel the same is still unclear. Ecological effects aside, I believe golf course executives should survey their patrons, and determine if golfers value the condition of the water bodies, and then evaluate possibly changing management techniques. If golfers genuinely value the presence of oligotrophic, compared to eutrophic, waterways, then I believe golf course executives should change their management practices to minimize the amount of nutrient enrichment that occurs in their bodies of water (Figure 8).

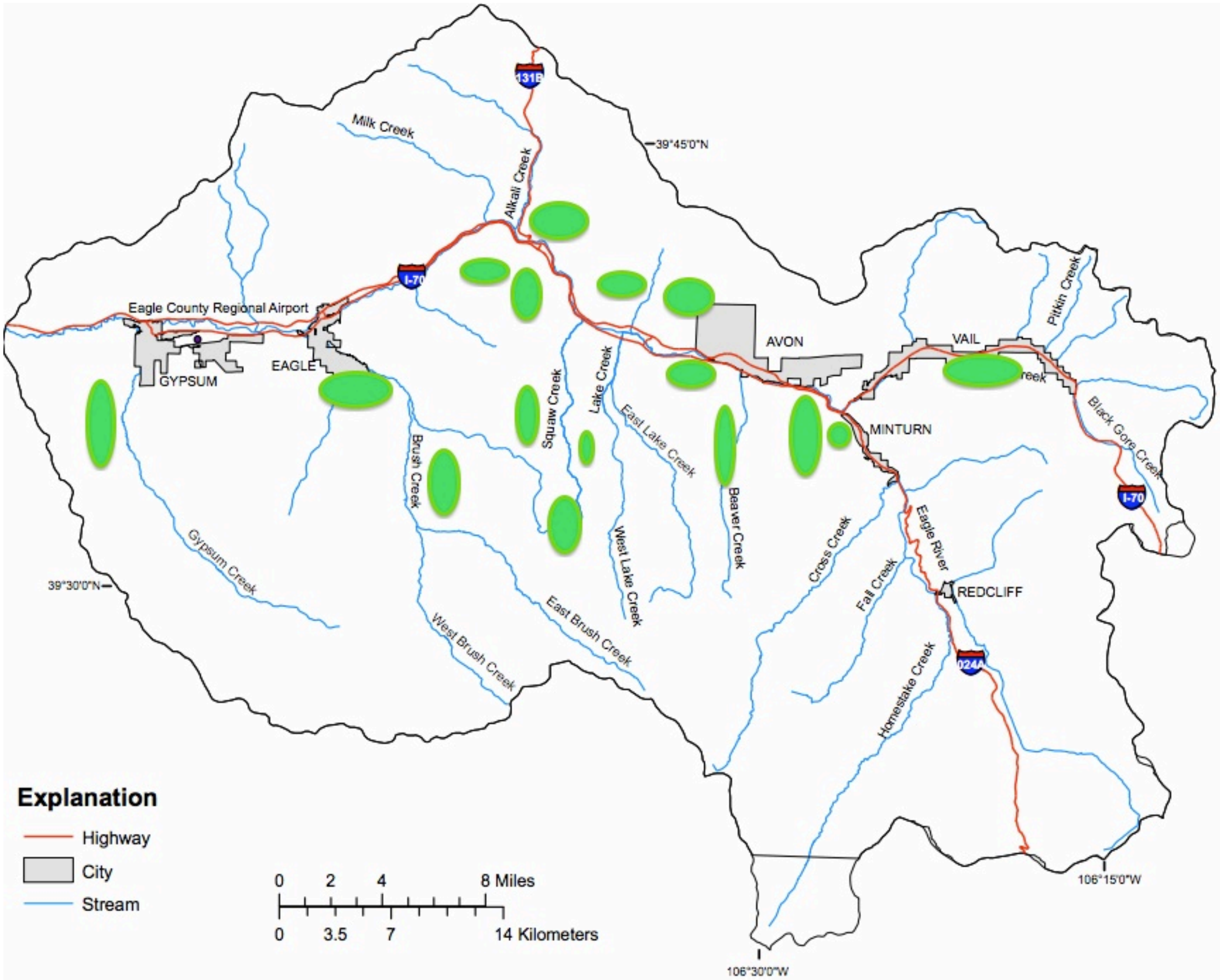

Figure 7: A map of the Eagle River Watershed boundaries with all golf courses. Each golf course that falls in the boundary is highlighted by a green oval. The exact locations of each course may be different than signified by the oval, but the locations are relatively accurate. The size of the ovals does not signify the size of the courses either, they are just meant to visually display the amount of golf courses in this particular watershed.

If there are not any ecological effects caused by fertilizer runoff, and people do not value oligotrophic waters, then I would not recommend courses to change management practices; however, I personally believe there is great value in having oligotrophic and pristine waterways, and I think most will agree. I argue that golf course waterways should reflect the condition of the turf. When the turf looks flawless and well maintained, so too should the waters. Allowing eutrophic waters to exist on a perfectly groomed golf course is like having a brand new luxury car with seats from your 1986 Honda Civic (at least in my eyes). I concede that not all bodies of water are naturally oligotrophic, and therefore I believe each course should determine what their ideal waterways look like, individually, after consulting with their patrons, and determine changes in management practices afterwards.

Figure 8: Photographs of two nearby lakes, less than 1 km away from each other. The top lake is on a golf course, while the bottom course is in a nearby neighborhood. This visual is meant to visually compare oligotrophic (bottom) and eutrophic (top) lakes. Do people value if golf course waters appear like the bottom versus the top lake? This should be an area of further research, for this field as a whole.

Conclusions

The results of my research help clarify the potential for golf courses to be a cause of eutrophication in aquatic communities. First, both TN and TP were significantly higher downstream from golf courses than upstream. The distance between each upstream and downstream sample site was small, and it is likely that golf course runoff is causing the increased nutrient levels downstream. During this research, I wanted to determine if golf courses in general could be an overlooked cause of eutrophication. I hypothesized: Aquatic communities downstream from Colorado golf courses exhibit TN and TP concentrations that are significantly higher than upstream concentrations, and downstream concentrations of TP and TN are higher than EPA recommendations, while upstream concentrations are not. I found that indeed, aquatic communities downstream from Colorado golf courses exhibited TN and TP concentrations that were significantly higher than upstream concentrations; however, not all downstream concentrations were above, and not all upstream concentrations were below, EPA recommendations. Only three out of eight courses exhibited downstream TN concentrations that were above EPA recommendations (Figure 4), and only five out of eight courses exhibited downstream TP concentrations that were above EPA recommendations (Figure 5). Also, one course exhibited upstream TN concentrations that were above EPA recommendations (Figure 4), and three out of eight courses exhibited upstream TP concentrations that were above EPA recommendations (Figure 5). From these findings, I believe that golf courses are still a potential source of nutrient enrichment in aquatic communities. As mentioned in the discussion section above, golf courses are large areas with vast differences between courses, which may lead to these differing results between each course sampled.

I conclude that even with these differences, golf courses cannot be ruled out as a potential source of nutrient enrichment. My results indicate that even over a relatively small number of courses, we see significantly higher nutrient concentrations downstream of golf courses than upstream. Consider this with the fact that there are 15,372 courses in the United States, and a total of 34,011 courses around the world, the effects of nutrient enrichment from golf courses could be vast (AP 2015). I will discuss the future research for this study below, where I will mention the next step for this research, and how fellow researchers can better determine if golf courses as a whole are contributing to eutrophication of aquatic communities.

The system I created to establish the environmental concern of each golf course could easily be replicated by golf course executives, business executives, and other leaders that are trying to determine sources of nutrient enrichment. With upstream and downstream nutrient concentrations, it is fairly easy to compare those values to EPA recommendations, the Dodds et al. (2002) limits, and calculate mass ratios of N/P. This study is unique because of the relevant Lewis and McCutchan (2010) paper, but this system could be easily replicated without a similar study. Communities, organizations, etc, could use this system to evaluate businesses, golf courses, and other like-places, and each place's environmental concern.

Recommendations

In this section, I will discuss how I would like to focus future research on the specific courses I sampled, with regards to the levels of environmental concern, established in the results section. Various strategies to minimize nutrient enrichment from golf courses will also be provided. I will conclude my thesis by discussing the future of golf course management, and the potential conservation opportunities golf courses can offer.

Follow-Up Research for This Study

Based on the levels of environmental concern for each golf course, I recommend the following future research. First, regardless of the level of concern I established for each course, I recommend course managers collect several upstream and downstream water samples throughout the upcoming golfing season, and send them to a laboratory to be analyzed for TN and TP, and chlorophyll a. This will give each course a more accurate indication of potential nutrient enrichment, compared to a one-time sample. The addition of chlorophyll a as a variable will help show the effects caused by these nutrients, as chlorophyll a is an indicator of algal biomass, which is a better indicator of eutrophication in moving water (i.e. rivers and streams) than turbidity (EPA 2000c). Second, as I mentioned above and again regardless of the level of environmental concern I established, I recommend conducting a survey of the patrons of each course to help determine if, aesthetically, oligotrophic water is important to golfers. Third, for courses that I determined to be environmentally concerning, I recommend implementing limited better management practices, while the course also collects more extensive water samples. Some strategies, all mentioned below, that are not labor or cost intensive, include lowering fertilizer rates, implementing native grass buffers, and even installing phosphorus removal structures (slightly more cost intensive). After the collection of multiple samples over the course of the next golfing season, all golf courses should implement better management practices depending on their water testing and aesthetic survey results. If the leaders of the courses I labeled potential and unlikely environmental concerns are worried about any of my results, I recommend they too implement limited remediation strategies, like the more environmentally concerning courses; however, I believe the courses of lower concern should focus on water sample collection and patron surveys, concurrently.

I believe in order to address the importance of golf courses and their threat to eutrophication, more studies like this one should be conducted. Are we overlooking a major source of nutrient enrichment? Collecting water samples from a large number (100-500) of courses would create a much larger sample size, and would allow researchers to make claims about golf courses in general as a source of eutrophication with much greater statistical influence than my results provide. Another smaller-scale study that could be conducted in response to this study could focus on collecting water samples from streams in similar areas, which do not have golf courses nearby. Locating streams in similar areas, and taking upstream and downstream samples with the same distance between samples, would allow the researcher to determine if the trends associated with golf courses are unique to the golf courses, or if they are common in the area. Golf course superintendents may want to consider collecting samples in this manner, in addition to the samples they collect throughout the golfing season.

Other researchers may take the results of a study comparable to mine, one step further, and also compare management strategies between courses. Each course in the world may fertilize, apply pesticides, mow the turf, etc, differently than all others. If management differences are leading to higher or lower nutrient levels between courses, the courses that are not leading to nutrient enrichment may be exhibiting exemplary management techniques, which other courses in the areas could attempt to replicate. This system may allow for even more nutrient enrichment lowering, when coupled with the strategies I mention below. Different management strategies may explain why Course H, a very high quality course, was one of the lowest environmental concerns, according to my determination system. I observed negative attitudes from professionals in the golfing industries, and these attitudes may lead to difficulties for future researchers attempting to obtain management information, however. A review of management strategies between sampled courses will give the researcher a better understanding of why there are different nutrient concentrations between sampled courses, and I believe this technique should be implemented in future studies similar to this one.

Strategies to Minimize Nutrient Runoff from Golf Courses

After surveying the ecological and aesthetic effects caused by golf course runoff, golf course owners and superintendents should consider various remediation strategies. Many efforts to control and limit nutrient runoff are underway on golf courses across the world. The three strategies I have observed to be the most common and successful are: implementing buffers, limiting application rates of fertilizers, and implementing multiple strategies.

One of the most popular remediation strategies is the implementation of riparian buffers. Riparian buffers are heavily vegetated land adjacent to water bodies (Mayer 2005). These areas act as filters for runoff by absorbing nutrients and lowering the amount of nutrients entering into water systems. The EPA conducted a literature review of riparian buffers and concluded that various types of riparian buffers are effective at reducing nitrogen in surface and groundwater systems (Mayer 2005). Another study of riparian buffers stated that a 0.5 kilometer buffer strip between a golf course and a creek efficiently filtered nitrogen and other nutrients, and helped promote ogliotrophic conditions within the creek (George et al. 2001). Although it would be impossible to implement a buffer of that size on a golf course, placing a buffer of that size between courses and major streams, could be successful in reducing nutrient enrichment on a larger scale. Implementing small turfgrass buffers may also lead to lower nutrient concentrations in nearby waterways. This is one very simple strategy, in which grass on the course within 5-10 meters from shorelines is not mown throughout the year, allowing for a buffer to grow, and filter nutrients (Davis and Lydy 2002).

In my literature review, many scientists recommended a common and straightforward remediation strategy: lowering fertilizer application rates. The amount of nutrients carried by runoff into surface waters is directly correlated to application rates of fertilizer, meaning that if you fertilize more, you'll cause higher nutrient concentrations in the water (Balogh and Walker 1992). Also, adding excess fertilizer to turfgrass does not guarantee higher biomass or greater success of the grasses (Wong et al. 1998). Techniques to reduce fertilizer usage and losses include: using smaller, more frequent applications, using slow-release organic forms of fertilizers, and only applying fertilizer when the soil moisture is low and precipitation is not expected for the next 48 hours (Davis and Lydy 2002; Shuman 2002). Lowering the application rates of fertilizers may also lower costs of maintenance for courses, another enticing reason to adopt this remediation strategy.

Reducing nutrient loading rates from golf courses to acceptable or safe levels may take more than riparian buffers and lower fertilizer rates, which is why many scientists are implementing and testing combinations of management practices. A three-year study was conducted in Kansas, where scientists introduced a variety of remediation strategies in an attempt to lower surface water contamination (Davis and Lydy 2002). Around the sides of waterways on the golf course, they allowed 10-15 meters of grass to grow uncut, creating a small, effective buffer (Davis and Lydy 2002). The scientists also relocated drainage to a filtration pond, allowing nutrients to sink to the bottom of the pond before discharging the water from the course (Davis and Lydy 2002). Davis and Lydy (2002) also increased the depth of many ponds on the course. The Red Carp was introduced into aquatic communities on the course to prey on and maintain the growth of algae and other microorganisms; however, as I mention below, golf course ponds should be viewed as potential ecological refuges, and introducing non-native species may not be the best strategy, ecologically speaking. After implementing these strategies and other minor changes, nutrient levels in the waters decreased below EPA recommendations, as the concentrations were previously above EPA recommendations (Davis and Lydy 2002).

In 2002, the House of Representatives held a hearing regarding how to promote the reduction of water pollution by corporations and organizations. The hearing discussed the effectiveness of a "water quality trading" system, similar to a cap and trade system for greenhouse gas emissions. This program could allow corporations and organizations to trade water pollution rights, presenting a voluntary and economically beneficial way to reduce water pollution (Subcommittee on Water Resources and the Environment 2002). This system has been effective in Idaho and other northern states, and should be considered and implemented on a much larger scale.

Another intriguing strategy is the introduction of phosphorus removal structures. These structures allow water to pass through a collecting duct that is filled with a byproduct of steel, know as steel slag, which absorbs phosphorus as the water passes through. Over a five-month period, this structure was able to lower the export of phosphorus into surface water by 25 percent (Penn et al. 2012). They also found that the already used steel slag could then be applied as a phosphorus fertilizer, since it had absorbed so much phosphorus while it was being used in the structure (Penn et al. 2012). I looked at an alternative study, where scientists were examining the implementation of a filter system and the ends of waterways on a golf course. These filters were effective at removing moderate levels of phosphorus, but ineffective at removing nitrogen (King et al. 2012). The scientists also observed that these filters were only effective during low flow events, and were very ineffective during storm surges or precipitation events (King et al. 2012). Many of the studies on remediation strategies were innovative and effective, and a combination of these strategies, if implemented correctly, could greatly reduce nutrient pollution from golf courses.

Golf Courses as Ecological Opportunities

I will conclude my thesis by discussing the future of golf course management, and the unique opportunities golf courses offer. Since 1780, 53 percent of all wetlands in the Continental United States have been lost or converted (Dahl 1990). This means that since 1780, the lower 48 states have lost 60 acres of wetlands every hour (Dahl 1990). With this occurring, species that occupy wetlands or other aquatic habitats have also lost over 50 percent of their possible habitat, with some species being affected more than others. Golf courses, however, almost always incorporate some sort of water feature, and present opportunities for the creation of new habitats for these species. Golf course waterways have typically been thought of as chemically stressed environments, unsuitable for most species (Colding et al. 2009); however with proper management practices, golf courses can shift from possibly causing ecological damage, to providing ecological refuge.

I reviewed many studies that support this claim. First, in a study done in Kansas in 1997, the researcher found golf courses and nearby avian (bird) habitats supported the same species richness (number of species found in a given area) (Terman 1997). Terman (1997) also found that golf courses were suitable habitats for threatened bird species, and building new golf courses can significantly increase the amount of suitable wildlife habitat in urban areas. Second, a team of scientists observed the survival to metamorphosis (tadpole to adult) rates of three different species of amphibians (Boone et al. 2008). They found that when reared in golf course ponds without bullfrogs or predatory fish (both predators) present, there were significantly higher survival to metamorphosis rates in Spotted Salamanders, American Toads, and Southern Leopard

Frogs, compared to nearby experimental reference ponds (Boone et al. 2008). Third, in Stockholm, Sweden, researchers found that golf course ponds provided habitat for threatened amphibian and macroinvertebrate species that were not found in other non-golf course ponds (Colding et al. 2009). They also concluded that golf course ponds were not chemically stressed habitats, as previously thought, but actually provided substantial, suitable habitat for wetland species, which is rare in urban settings (Colding et al. 2009). Hodgkison et al. (2007) studied suburban golf courses in Australia, to attempt to quantify the conservation value of golf courses. Some golf courses they examined provided desirable habitats for many regionally threatened vertebrates, especially birds and mammals, and pond networks on these courses even acted as refuges for wetland bird species (Hodgkison et al. 2007).

The beneficial ecological potential of golf courses is great; however, as one study noted, while "golf courses evidently have the capacity to act as a refuge for a range of threatened wildlife, most only support common urban-adapted species, and therefore fail to realize that potential," (Hodgkison et al. 2007). In an increasingly urbanized world, golf courses may become more and more important ecologically, especially in urban areas, and are especially important as aquatic refuges (Boone et al. 2008; Colding et al. 2009). As my committee member Dr. Pieter Johnson said to me, "We'd all rather see golf courses than parking lots," (Johnson person. comm. 2015). Golf courses do not have to be environmentally damaging, but instead provide immense ecological opportunities. Now the golfing and ecological communities need to work together, and capitalize on the unique opportunities they are presented with.

Appendices

Appendix I: Field Observations

The first sample site was downstream of Course A, after the creek has gone downhill through multiple holes at Course A. The water clarity was hard to distinguish, because it was not very deep; however, there were many aquatic plants and algae on almost every hard surface in the water. The overall tint was green, and all the rocks were covered in algae or plants. I did not notice any wildlife in the stream, and I doubt it was supporting anything but macroinvertebrates (insects). The water was fast moving, with no stagnant areas. This stream fed out of a 50 m^2 wetland, with many willows, cattails, and other like plants. I did not get to see the condition of any bodies of water on the course. The upstream sample site varied slightly from the downstream site. When we arrived, I was surprised to notice that the water was somewhat murky. I could not see the bottom, but took the depth using the thermometer and fly-fishing line. I did not see any evidence of aquatic plants or algae, but that could just due to the low water clarity. There were also abundant grasses along the shoreline, with many falling into the water. I did not see any wildlife in or near the surface. The flow was fast, with a series of pools and riffles, which was separated by fallen trees or other debris.

I determined the downstream sample site of Course B after consulting with both the superintendent of the course and a member of the club. The site was the discharge of a drainage pipe, which ran underneath a road and emptied into a ravine, from a pond on the first golf hole. Where the pipe emptied, it was relatively deep with a variety of wetland plants, including dense willows. Because of these plants, I could barely find where the pipe started, and it was hard to make any qualitative observations about the water quality. I could see fallen leaves, along with a white, foamy film floating on the surface. I could not see any animals, but from my years of fishing, I suspected there would be some fish living there, and that area looked prime for macroinvertebrates. It was relatively deep, as I had to fully submerge both arms to take the sample I wanted. The water coming from the pipe was flowing very rapidly. Before taking the upstream sample, I observed three large (50-200 m^2) lakes on three consecutive holes at Course B, and noted the condition of each. Those lakes looked very unattractive, especially when looking at a nearby lake (Figure 8). This course has traditionally been very well maintained. The superintendent also recommended the upstream sample site. It was an irrigation ditch, which is diverted off of a nearby creek that provides water for the neighborhood around Course B. The water was very clear, and I could easily see everything in the water. There was some debris in the water from nearby trees. I saw a water strider on the surface, but no other wildlife. The flow was also rapid, but slower than the downstream site.

The fifth sample site was upstream of Course C. The water upstream was relatively clear, but not as clear as I expected, based on other upstream sites. There were some algae and aquatic plants present in the water, which I hadn't seen at any other upstream site. The water was moving very fast, and it was flowing sufficiently downhill, with a series of pools created by rocks and woody debris. I did not get a chance to look at any other parts of this creek, so I could not compare whether that algal growth was common. I did not see any wildlife, but it was large enough for fish, and likely supports many macroinvertebrates. I observed two ponds on the course from a distance, with one possessing a surface algal bloom (around 1/8 the pond area). Course C is a very expensive course, and they keep their grass tightly mown as well. The course has large changes in elevation, with rolling grass hills, comparable to Course D. The particular stream of interest was on average 1-3 m wide, and was surrounded by 0.5 m tall grass on both sides, acting as a buffer. The buffer was twice as wide as the stream, as if the stream was the middle third of the buffer. The downstream water looked relatively clear, but again, it was hard to tell because it was very shallow. There was an extremely large amount of algae, and other aquatic plants, almost covering the entire creek bottom. I was surprised by how much was growing in the creek. Also, I observed where this creek entered into a larger creek, and the larger creek was really clear, with hardly anything growing, while this creek possessed abundant green plants. I did not see any wildlife, and I doubt anything other than insects could inhabit the downstream site. The water was flowing quickly, but not as fast as upstream.

Course D, the EagleVail Golf Club, is the course where I developed this whole idea. For the downstream site, I decided to sample from a site on the course, because there was a 10 m rock waterfall before the stream emptied under a road and into a large river. This site gave me the most interesting of all of my observations. Apparently, there used to be dense algae or aquatic plants, but it all appeared to have died off, and became brown or lifeless (eutrophication perhaps?). To investigate further, I walked a little upstream from the downstream sample site, and there were massive aquatic "plant carpets," and other aquatic plants throughout the creek. Because I observed this only fifty meters up from the sample site, I wondered if I witnessed a dead zone. I did not see anything living in the creek at the downstream site, as the whole thing was extremely clear, but it appeared that nothing was moving or alive (Figure 3). In my years of playing Course D, I have observed many trout in this creek and a variety of macroinvertebrates. The flow downstream was more of a "meandering" pace, with a series of large rock waterfalls. Course D has a large amount of running water throughout the course, more than most other courses. The creek I sampled also widens into a series of ponds throughout the course. I have noticed that on some of the flatter golf holes, there are large numbers of aquatic plants, and some surface algae, but the upstream water is always very clear. Most of the water systems on Course

D have a 1-2 m buffer of untrimmed native grass; however, there are areas (Hole 16) that have a really tight mow line (short grass), right into the water. The sample stream flows through 10 of Course D's holes, running close to the golf turfgrass, at all times. This course is very mountainous, with steep holes and sloped greens. The grass is longer than at most courses, which may slow some nutrients from entering into the water. The upstream sample at Course D had very clear water. I could see everything in the water, even to depths of 40 cm or so. There were no aquatic plants that I could see, other than very small green specks on a few rocks. Some mosses were growing on many rocks, but stopped at the water line, or just below it. An insect hatch was occurring while we were sampling, and many insects were coming off of the water, and flying nearby. This water was very cold, and was moving downhill very quickly downhill.

The upstream sample at Course E was in a little stream that runs through Boulder County Open Space, before going through a pipe, and into the golf course. Some of the water that did not go into the pipe went into a nearby ditch, which then flows into South Boulder Creek. This inflow pipe feeds all of the ponds on the last nine holes at Course E, and the water that flows in through this pipe eventually flows out at the downstream site. The water upstream appeared clear, as I could easily see the bottom; however, it was pretty shallow so I couldn't get a great gauge on clarity. I did not notice any algae or aquatic plants where I sampled, and the shoreline was lined with grasses, some falling into the stream. I did see a dragonfly near the water, as well as smaller macroinvertebrates. Two deer ran off into the open space as I approached the stream. I also noticed the presence of tadpoles in the nearby ditch. I have seen both frogs and turtles within the lakes in Course E. The water was meandering and did not have a particularly fast flow. I have seen many bodies of water on this course, and a few times I have noticed algae in creeks when they were running low, as well as concentrations of algae focused around lake outflow areas. I do remember that the lakes are always very murky, and the visibility is not more than a 1 m into the water. Typically, the lakes around the course do not have buffers on the areas adjacent to holes. For example, along the fairways (the middle of golf holes) there is usually no buffer, but behind a tee box (the beginning of golf holes), there are some native grasses that make up buffers. Course E has an extensive lake/stream system that flows through many of the last nine holes. The downstream sample occurred where the lake/stream system drains out of the course. The water was pretty murky at the time I sampled, with many pieces of woody debris and leaves in the water. I did see a little algae and aquatic plants in the water. I did not see any wildlife in the water, but I would expect that this would typically support macroinvertebrates. The lack of wildlife could be due to the low volume of the stream. The flow was relatively slow, and was just moving with the downhill gradient. I did remember that this site smelled pretty unpleasant, which may or may not be associated with aquatic organisms.

At Course F, there were many NO TRESSPASSING signs all over the sample areas, so I didn't get as close to the course as I would've liked. The waterway I sampled appeared to be more of a canal and less of a natural occurring stream, and I wondered what effect this might have on my results. This water was extremely murky. It was only about 15 cm deep, and you couldn't see the bottom. There were lots of leaves in the water, and this water was pretty unattractive overall; the secretary at the CSU lab even picked up the sample and said, "ew, this one is yucky." I did notice water striders on the surface, but the clarity and overall condition of the water made me doubt that any large organisms were living in this. The flow was very slow. Based on the very small areas of the course I could see, the course appeared to be in great shape. The waterways were lined by 1-2 m buffers, which started when the turfgrass began to descend into the water. This course is designed on a similar landscape to Course E, and appeared to be relatively flat, with little topographical features; however, that was only based on my observations driving around it. I chose this course because this particular stream flows through much of the course, and much of it is in contact with fairways or other short turfgrass areas. The water in the upstream area was also murky, but not as much as the downstream site. There were floating leaves in the water, as well as shoreline grasses that were falling into the water. The water was much deeper here, and was moving quickly. This stream was diverted into a network of canals and ditches nearby, and there were extensive fences guarding this area. I did not see any wildlife, but I assume this could be a source of macroinvertebrates, and maybe even fish, due to its greater depth. This sample was not taken in the middle of the stream, but was very close, and was taken at mid depth.

I sampled the middle of a large creek at the end of the Course G. The water was fairly clear, I could see the bottom everywhere, but clarity decreased with depth. I did notice algae and aquatic plants growing in the creek, but they were not abundant. There were many macroinvertebrates flying near the surface, and I suspect that there was fish in this creek. The creek was moving very fast, with sufficient riffles throughout the creek. I couldn't see the condition of bodies of water on the course, or buffer areas; however, I did spot some floating substances, possibly algae on a lake from 0.5 km away. The course looked very well manicured. This course did have a bit more slope to it than the previous two. There were rolling hills throughout the course, and it is designed on a slope coming down from a large reservoir, giving it more slope. My downstream sample site was actually downstream of some of the course, but it is very unlikely that this site was contaminated by golf course runoff. I also did not take this sample from mid-stream, mid-depth, because the water was very deep and very wide. I took it 5 meters from the right side (looking upstream) of the stream, at a depth of 1 meter. This water had limited clarity, to about 2 meters. There were lots of algae, or moss-looking plants, growing on submerged rocks. Macroinvertebrates were flying all over the surface and nearby the water. There was also a sign for fisherman parking, so I assume there are fish in the water. The water was hardly moving.

My downstream sample site at Course H appeared to be clear, but it was very shallow, so it was hard to tell clarity. I did notice some algae on some rocks, but not as much as I expected. I did not see any wildlife in or nearby the water, but I expect that macroinvertebrates inhabit this creek. The flow was relatively slow, but still moving with the slope of the creek. This course is arguably the best course in Colorado, from most golfers' points of view. The course has very fast greens, with no buffers on any of the waterways. The course also has a lot of slopes, and interesting topography all over the course. There were some very severe slopes that went directly into the sample creek, and these had very tightly mown turf all the way to the shoreline. The course is unbelievably beautiful and well maintained. It hosted a PGA Tour event this year, the US Amateur in 2013, and US Open Championships in the past (major golf tournaments). The upstream site at Course H had water that was slightly murky, but I could still see the bottom everywhere. Where the water was moving a little faster, I could see some algae and aquatic plants. I noticed many macroinvertebrates flying near the water, and I think this area could support fish. I sampled where it was slow moving, but it began to go downhill over a series of riffles, before it entered the course. I would also like to note that I attended the PGA event this year, and observed many of the water bodies. The course is famous for a lake on holes 17 and 18, and I did not observe any algal growth in the water.

Appendix II: Aerial Photographs

Figure 9: Aerial photograph of Golf Course A, courtesy of Google Earth.

Figure 10: Aerial photograph of Golf Course B, courtesy of Google Earth.

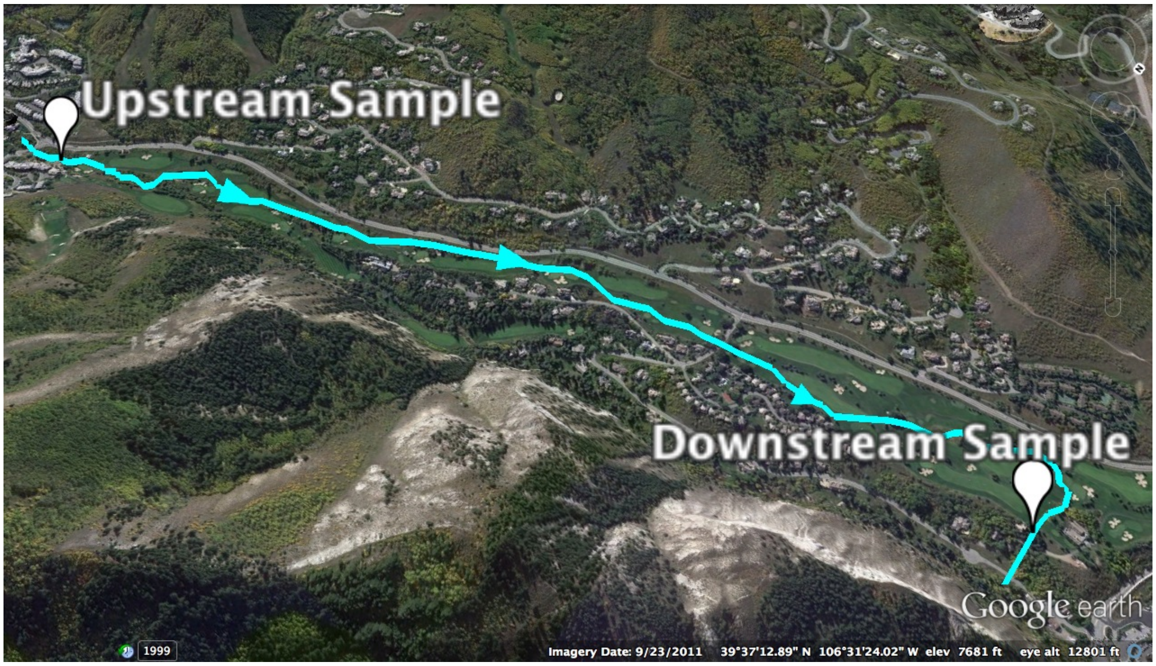

Figure 11: Aerial photograph of Golf Course C, courtesy of Google Earth.

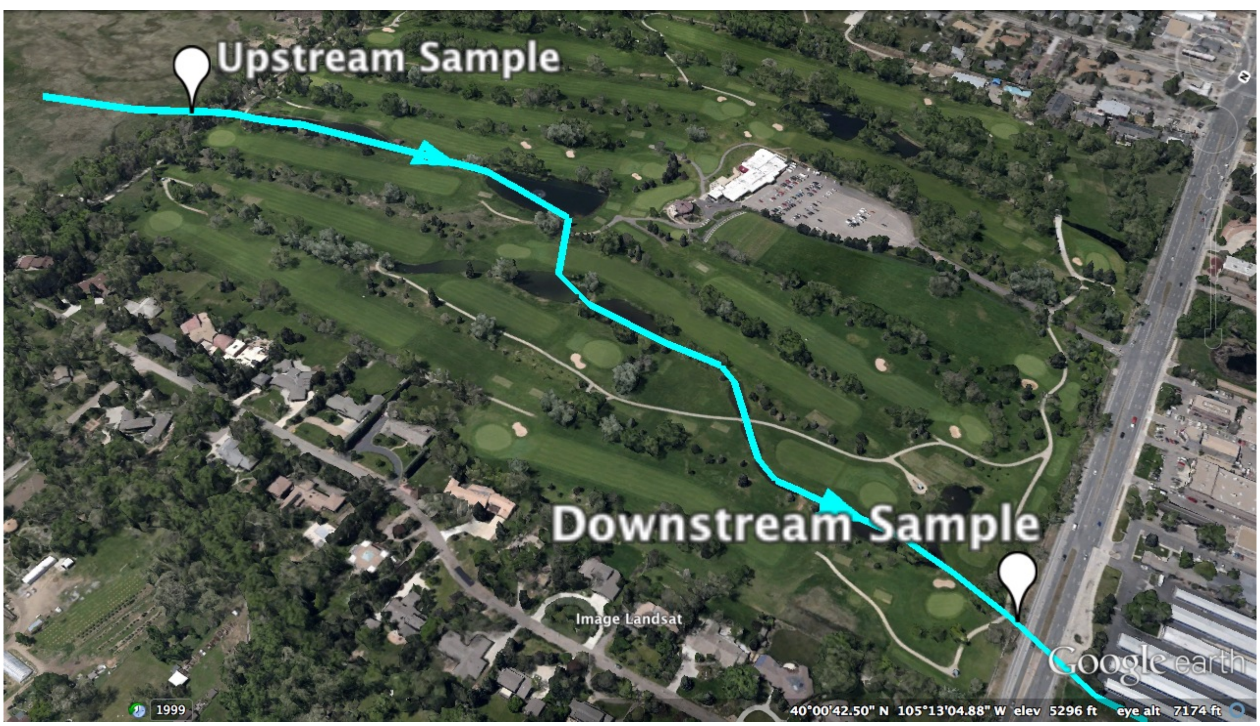

Figure 12: Aerial photograph of Golf Course E, courtesy of Google Earth.

Figure 13: Aerial photograph of Golf Course F, courtesy of Google Earth.

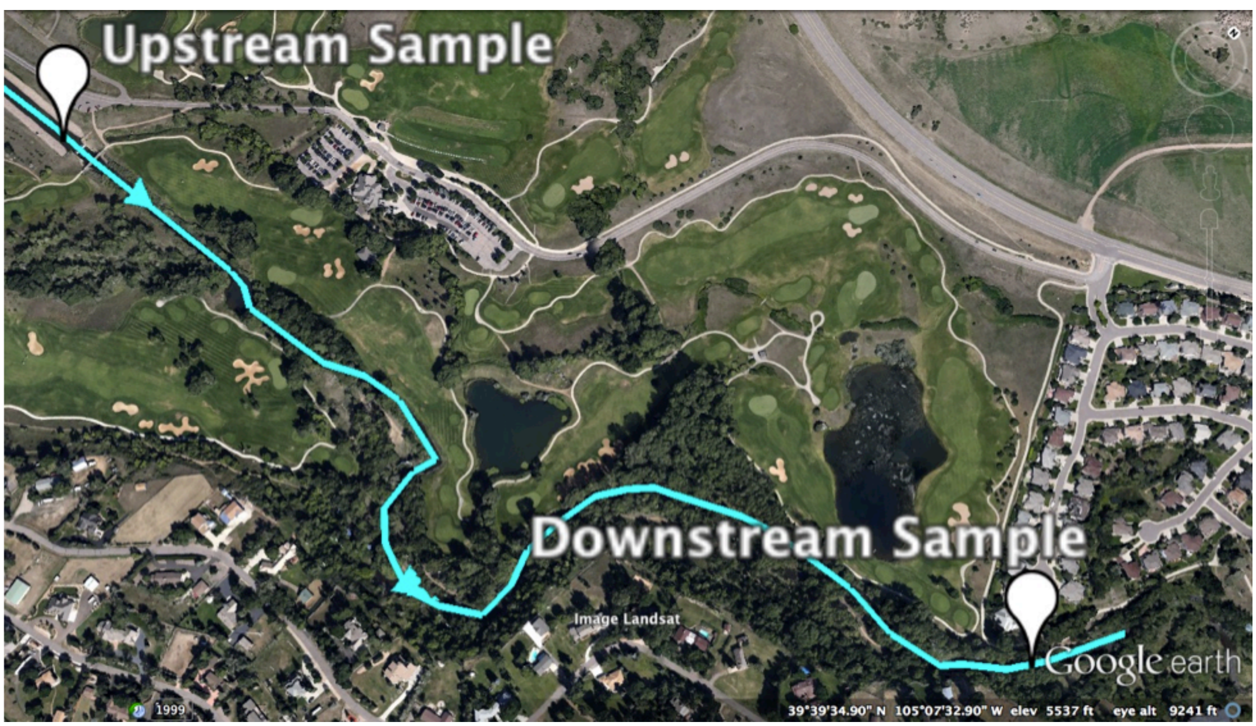

Figure 14: Aerial photograph of Golf Course G, courtesy of Google Earth.

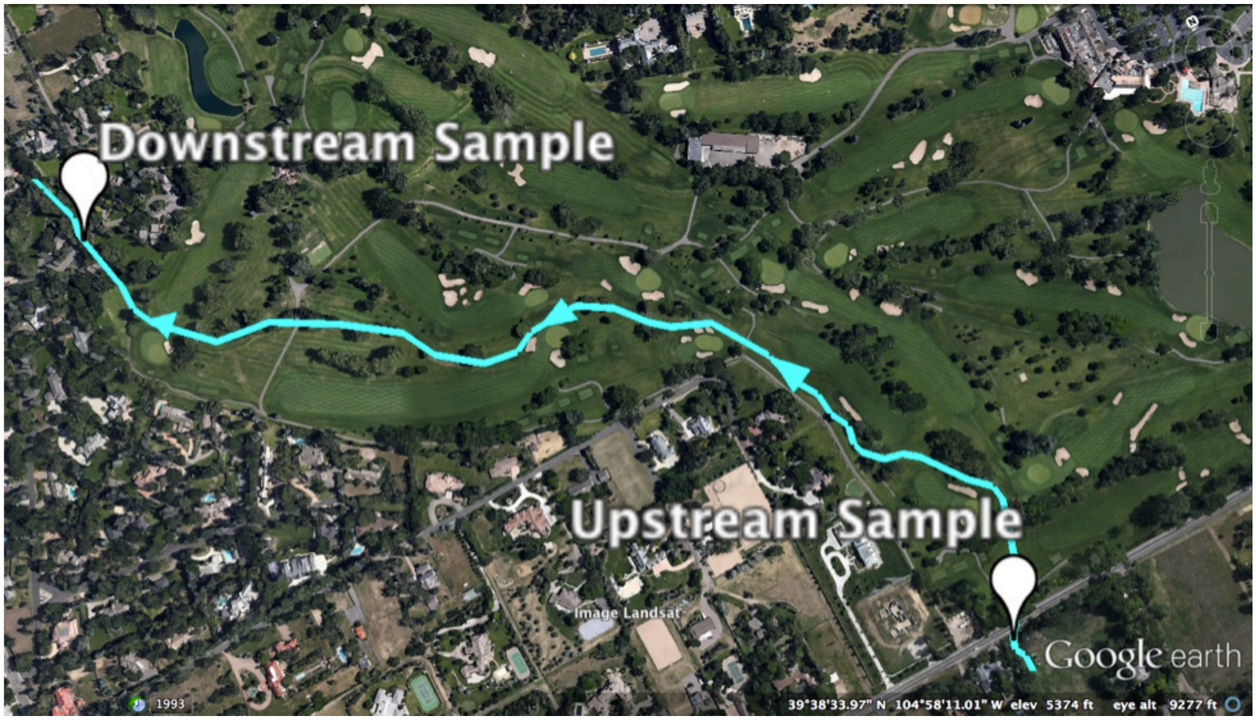

Figure 15: Aerial photograph of Golf Course H, courtesy of Google Earth.

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